GRAIN SORGHUM RESPONSE TO WATER SUPPLY AND ENVIRONMENT

by

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Abstract

Sorghum [*Sorghum bicolor* (L.) Moench] has greater drought resilience than many other crops, producing food in the most stressful environments. Sorghum is a reasonable crop choice for farmers working with limited-water supply. The objective of this study was to compare sorghum hybrids differing in yield strategies under varying water supply environments. Yield, biomass, grain harvest index (HI), and yield components (seed number and seed weight) were compared in both rainfed and irrigated situations. Field experiments were established in 2014 and 2015 at Topeka, Scandia, Hutchinson, Garden City, and Tribune, KS. Three sorghum hybrids (Pioneer 85Y40, Pioneer 84G62, and Dekalb 53-67) with different yield potentials at varying water supply were studied. Hybrids 85Y40 and 84G62 tended to have greater yields than hybrid 53-67 when the environment's average yield level was greater than 8.5 Mg ha^{-1}. The opposite scenario where hybrid 53-67 had greater yields than the other two hybrids tended to occur for environments yielding less than 8.5 Mg ha^{-1}. Both biomass and HI were significantly correlated with grain yield (r values of 0.62 and 0.32 respectively), with biomass having an overall stronger correlation than HI in all environments. In yield group 3 (<8.5 Mg ha^{-1}), biomass was much more strongly correlated (r=0.85) to yield than in the yield groups 1 and 2 (>9.5 Mg ha^{-1} and 8.5-9.5 Mg ha^{-1} with r values of 0.35 and 0.52 respectively) suggesting that biomass production is of utmost importance for yield production in drought prone environments. Harvest index on the other hand had a much stronger correlation with yield in group 1 (r=0.62) when compared to group 2 and 3 (r 0.13 and 0.36 respectively) showing the importance of not only biomass, but also of HI to maximize yield in high yielding environments. Hybrids 85Y40 and 84G62 had larger HI values relating to the yield trends in the highest yielding environments.

Seed number had a stronger correlation with yield (r=0.77) than seed weight (r=0.37) supporting the importance of increasing seed number to improve yield in sorghum.

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Chapter 1 - Literature Review

Broad Overview

Sorghum [(*Sorghum bicolor* (L.) Moench] is an important crop primarily used for feed, fiber, food, and ethanol production in the United States (US). The US is the leading sorghum producer and largest exporter in the world, with Kansas as the leading producer in the US (USDA, 2015). In 2014, 2.6 million hectares were planted to grain sorghum with a total production of 11 million metric tons (USDA, 2015). Sorghum has greater drought resilience than many other crops and is used for food in developing countries because the yields are more stable than many other crops. In areas where fertilizer and water is limited, sorghum can still produce grain with less favorable growing conditions. Projected population growth to 9 billion by 2050 poses a great challenge in food production, forcing agriculture to produce more grain with the available natural resources such as water (Rakshit et al., 2014). Irrigation water supplies, especially in western Kansas, are declining pushing the agriculture system to change and adapt to the forthcoming challenge. In areas where water is scarce and/or irrigation is limited, sorghum could be a good crop option to fill the role of producing more grain per unit of water use.

Future climate change will impose a challenge to agriculture connected to greater frequency of unfavorable growing conditions such as drought and other extreme events (e.g., heat, flooding, etc.). Therefore, selecting more resilient crops will be needed in areas prone to drought or other abiotic stresses (Emendack et al., 2011). Grain sorghum is a C4 crop with a high degree of resiliency to drought and heat prone environments (Rakshit et al., 2014). This will be extremely important if climate change affects crop production and increases heat and drought stress in crops. This study is designed to look at varying commercial grain sorghum hybrids and how they respond across different environments (weather plus water supply variations).

Genetics

Genetic improvement and breeding play an important part to increase yields in any crop. Average sorghum yields have increased at a rate about 3 times less than that of corn yields primarily due to the slow improvements in genetics and a low investment in plant breeding in sorghum as compared to corn (Mason et al., 2008). Average annual US sorghum yield increase from 1957 to 2008 was 45 kg ha^{-1} yr^{-1} for dryland with no significant yield increase under irrigation while corn from 1939 to 2009 has had a 90 kg ha^{-1} yr^{-1} and a 120 kg ha^{-1} yr^{-1} yield increase for dryland and irrigation, respectively (Assefa et al., 2014). Two-thirds of the yield improvement in grain sorghum can be attributed to agronomic practices rather than genetics (Mason et al., 2008). Because of the greater improvement in corn yields, there has continually been less acres planted to sorghum and an increase in acres planted to corn (Mason et al., 2008). This shift in acres planted can also be attributed to increased drought and stress resistance in corn (Nissanka et al., 1997). Notwithstanding the successful genetic corn improvement, sorghum appears as a better option in environments subjected to abiotic stresses such as drought and/or heat either from a yield or an economic advantage due to lower production costs (Staggenborg et al., 2008).

Although corn has increased yield and improved more than sorghum, with possible advances in sorghum breeding and genetics, a new interest in planting more acres to sorghum could arise. Steps have been taken to improve genetics in sorghum. Since genetic diversity is important to crop improvement, the USDA partnered with Texas A&M to create a program to bring in lines from Africa that could be used for sorghum production in the United States (Smith et al., 2010). Improvements in yield depend on the seed weight and seed number produced by the plant (Maman et al., 2004). Recent research has found a mutant that increases seed number by setting three fertile spikelets on each spike instead of just one (Burow et al., 2014). Based on initial observations documented by the previous authors, utilization of this seed number trait could potentially produce a 30 to 40 percent increase in head seed weight (Burow et al., 2014) primarily via improvement of total number of seeds per head.

Yield Components

Grain sorghum yield components and physiological mechanisms for yield formation illustrate some of the limitations and prospects for yield improvements. An important efficiency term is the grain harvest index (HI). Grain HI is determined as the ratio of the grain yield to the aboveground biomass when the crop reaches physiological maturity. Emendack et al. (2014) claims that the ceiling for maximizing grain HI is close to being attained for intensively bred crops. Harvest index greater than the optimum limit will likely create a yield reduction due to a decrease in biomass and the ability for the plant to produce carbohydrates to translocate to the grain (Emendack et al., 2014). For grain sorghum, typical grain HI was reported to range from 0.3 to above 0.5 (Steduto et al., 2012) with the larger values being achieved as more water is consumed during grain filling (Routley et al., 2012). Maximum genetic potential for grain HI in current commercial sorghum hybrids has been reported to be approximately 0.55 units (Hammer and Broad, 2003). The grain HI ceiling is tightly connected to the transpiration level, with grain HI leveling off around 0.55 units when transpiration reached 300 mm (Tolk and Howell, 2009).

In grain crops, the goal is to increase grain yield. Maximum grain yield can be attained by utilizing multiple physiological strategies. Hammer and Broad (2003) showed that larger yields were attained by achieving both greatest total aboveground biomass and HI, but lower yields were correlated with less biomass for some studies and smaller HI values in other studies. Hammer and Broad (2003) also found a tendency for later maturing hybrids to have a smaller HI that don't necessarily relate to decreased yields due to an offsetting increase in biomass. A study in Nebraska showed that both seed number and size had significant correlation with sorghum grain yield (Maman et al., 2004).

Sorghum responds to different environmental conditions throughout the growing season that can either increase or decrease yield. Grain sorghum responds to better conditions and adequate rainfall by increasing tillers per plant thus increasing panicles per area (Baumhardt and Howell, 2006). When drought stress impacts the plant between panicle initiation and flowering time, number of seeds set could be greatly reduced, but if the stress occurred after flowering, then the seed weight could be potentially impacted (Baumhardt and Howell, 2006).

Water Use Efficiency

When it comes to drought tolerance and water use, there are differing viewpoints and opinions as to what confers greater drought tolerance. Increasing water use efficiency (WUE) is one idea to increase drought tolerance (Kapanigowda et al., 2012). The term WUE can be defined as aboveground-biomass to water use ratio (slope of the relationship) (Steduto and Albrizio, 2005). A similar term for this process used in literature is transpiration efficiency described as the ratio of biomass produced to the amount of water transpired (Tolk and Howell, 2009). Some common viewpoints are that if the water use efficiency increases, then drought tolerance increases because there is a greater ratio of crop yield to water use. Water use efficiency can increase by either an increase in biomass produced or a decrease in water used or a combination of the two (Narayanan et al., 2013). Differences in WUE have been found among differing genotypes of grain sorghum (Kapanigowda et al., 2012). A recent study performed in

Kansas suggests that WUE in sorghum was the outcome of an increase in biomass rather than a decrease in water use, resulting in possible increases in WUE without decreasing yield or biomass potential (Narayanan et al., 2013). The opposite idea to increasing WUE or transpiration efficiency for greater drought tolerance states that water used for transpiration should be maximized since transpiration is the driving force to increase biomass production (Blum, 2009). A direct linear relationship has been shown between both yield and biomass to transpiration (Tolk and Howell, 2009), and that this relationship of biomass produced is linear with the amount of water used whether in wet or dry conditions (Steduto and Albrizio, 2005). High yield potential is not always related to high WUE as many cases of increased WUE have a reduction in water use rather than an increase in yield (Blum, 2005). Different genotypes of sorghum have been shown to have differing WUE (Donatelli et al., 1992), showing a need for breeders to select for both WUE and biomass production (Narayanan et al., 2013).

Water use efficiency of a crop production system has many parts in the chain of events besides the transpiration efficiency of a genotype (Hsiao et al., 2007). Although transpiration efficiency of a genotype is important, other practices and parts to improve the overall WUE of the entire system are also important (Hsiao et al., 2007). No-till systems and more residue cover could help retain moisture during the fallow period for the next crop, increasing WUE due to less evaporation and runoff and greater water infiltration (Stone and Schlegel, 2006). Other strategies to be more efficient in water use are through shorter fallow periods, crop selection, and choice of crop rotation (Stone and Schlegel, 2006). A common example in the western Great Plains of using water more efficiently would be in areas where the traditional crop rotation is winter wheat and fallow. The precipitation use efficiency is poor in the summer during the fallow when more rainfall is accumulated (Maman et al., 2003). To help improve this, another crop can be planted in the fallow period to improve the efficiency of water use.

Stresses

The two environmental stresses that cause the most common yield reduction is sorghum are heat and drought. For sorghum, the period bracketing flowering and the grain filling are the most sensitive times to abiotic stresses (Emendack et al., 2011). Heat stress can play a major role in grain sorghum yield potential (Mahama et al., 2014). The most sensitive period to this stress was found to be during pre- to early post-flowering interval (Prasad et al., 2015). Sorghum is very sensitive to high temperature stress during the flowering stage because of the damage caused to pollen (Djanaguiraman et al., 2014). Even though sorghum is considered more drought tolerant, drought and heat stress at and around the flowering stage greatly reduces yield (Hussein and Alva, 2014). Drought and heat stress shorten the length of grain filling leading to a smaller seed weight (Mahama et al., 2014). Yield reduction from high temperature and drought stress occurring before flowering results from a reduction in total seed number, but if these stresses occur after flowering, a reduction in seed weight causes the lower yields (Prasad et al., 2008).

Drought Mechanisms

Overview

Drought causes crops to have a reduction in yield compared to their genetic potential (Mitra, 2001). Drought tolerance is the ability of a crop to produce a high yield under water deficit conditions compared to non-limiting water conditions (Mitra, 2001). Sorghum has better drought tolerance than other cereal crops (Assefa et al., 2010). Although sorghum can withstand drought better than other crops, there is not a crop that is not affected by drought. Drought stress limits crop yields most severely in semi-arid regions of the world (Afshar et al., 2014) and can cause other problems like disease (Assefa et al., 2010). Drought tolerance is a complex process that involves morphological, physiological, and biochemical processes (Beyene et al., 2015). Most adaptations to drought are speculated to come along with a cost that has disadvantages in productivity (Mitra, 2001). There are four mechanisms for drought response by plants: drought avoidance, drought tolerance, drought escape, and drought recovery (Fang and Xiong, 2015). The two major mechanisms used by crops are drought avoidance and tolerance which refer to the plant's ability to maintain a higher water potential and the ability to maintain functions under a lower water potential, respectively (Fang and Xiong, 2015). Drought occurring before flowering reduces seed number by reducing plant stands, tillering, number of heads, and/or seeds per head; but drought after flowering reduces seed size by reducing transpiration efficiency, CO_2 fixation, and carbohydrate translocation (Beyene et al., 2015). Emendack et al. (2014) postulated that high grain HI is a good predictor for pre-flowering drought tolerance and grain yield.

Morphology

Root growth and structure is of upmost importance for exploring the soil profile for water extraction during periods of water limitation (Singh et al., 2010). The root system of sorghum can explore as deep as 2.5 m in the soil profile and can be very dense because sorghum has more secondary roots per unit of primary roots than other crops (Assefa et al., 2010). When compared to corn, sorghum roots have a greater mass percentage in the upper soil profile, with longer lengths exploring deeper sections of the profile (Assefa et al., 2014). In well-watered environments, newly formed sorghum roots near the surface act as a sink for carbon, creating a more lateral and dense root system; whereas in drought conditions, the older roots act as a carbon sink, creating longer roots to explore deeper down into the profile (Blum, 1996).

Within sorghum, there are some root traits that make certain lines or varieties more drought tolerant than others. Characteristics such as root length, density, mass, volume, and thickness are highly correlated with drought avoidance (Beyene et al., 2015). Root architecture is also a valuable trait to look at for drought avoidance, because a narrower root angle allows for deeper root penetration and a faster elongation rate (Singh et al., 2010). Genetic improvements leading to an increase in grain yield were achieved parallel to an increase in root biomass and water uptake (Assefa and Staggenborg, 2011). Along with the root traits, the plant reduces its leaf area during drought stress to minimize water loss by reducing leaf growth and senescing older leaves (Blum, 1996). Sorghum also will produce a thicker waxy cuticle to prevent water loss (Assefa et al., 2010).

Physiology

In addition to possessing root traits associated with drought avoidance, sorghum is a C4 plant, in which the photosynthetic pathway allows for greater water use efficiency. The C4 plants have a greater transpiration efficiency than C3 species because C4 photosynthesis is more efficient in warm temperatures (Xin et al., 2009). Plants that use C4 photosynthesis are better suited for drought and heat because they concentrate CO_2 in their leaves so that photorespiration is minimized compared to C3 plants (Ghannoum, 2008). Even among C4 plants, sorghum can keep its stomata open under greater drought stress than other crops like corn (Assefa et al., 2010). With the combination of root structure and stomata opening, sorghum is able to manage water stress better than corn (Assefa et al., 2014). Sorghum will roll its leaves to decrease radiation intensity (Assefa et al., 2010) although it is believed that more drought tolerant lines have less leaf rolling and lower stomatal conductance (Beyene et al., 2015). Sorghum’s ability to produce solutes for osmotic adjustment contributes to its greater drought tolerance (Santamaria et al., 1990). Increased osmotic adjustments to drought stress before and after flowering have less of a decrease in yield compared to smaller osmotic adjustments (Ludlow et al., 1990). Sorghum will create smaller vacuoles from the larger vacuoles when the water potential in the cell drops which helps the tonoplast of the vacuoles to maintain their function of keeping the cell turgid (Assefa et al., 2010). When there is water stress before the onset of flowering, sorghum can go into physiological dormancy and stay in a vegetative growth stage until favorable conditions arise (Stone and Schlegel, 2006). Blum (1996) postulates that a hormonal response regulated by abscisic acid (ABA) is one of the main mechanisms involved in the regulation of sorghum growth being delayed when drought stress occurs.

Stay Green Trait

Nitrogen (N) is the one of the most limiting nutrient in grain sorghum and has a positive effect on grain yield from N application (Mahama et al., 2014). Sorghum varieties that stay green longer into reproductive stages are shown to have better N utilization (Borrell et al., 2000), better drought tolerance, reduced lodging, and greater resistance to stalk rots (Beyene et al., 2015). Stay green in sorghum is a result from having more N in the leaves during grain filling compared to senescent sorghum (Borrell et al., 2001). Evidence suggests that stay green types extract more soil N during grain filling (Borrell et al., 2001) and have a greater green leaf area at maturity than senescent types (Borrell et al., 2000). The reduced leaf senescence after anthesis allows for continued photosynthesis through grain filling and delayed senescence under drought stress (Beyene et al., 2015). Borrell et al. (2014) suggests that the stay green trait affects root growth and architecture but also decreases canopy size at flowering related to water conservation purposes. This is important because roots reach their maximum potential size at flowering as growth ceases (Beyene et al., 2015). Yield improvements for the stay green trait have been consistent during drought stress, but have been inconsistent with adequate rainfall. Tolk et al. (2013) reported that a stay green sorghum hybrid was able to produce a greater yield compared to the senescent hybrid by keeping greater seed numbers under stressed environments, but the same stay green hybrid had a lower yield under non-stressed environments. Another study's results agree that stay green has a yield increase and greater resistance to lodging in drier years in response to post-anthesis drought stress, but stay green did not show any yield disadvantage during wetter years (Borrell et al., 2000). Not all stay green traits are necessarily beneficial for yield (Borrell et al., 2014). For example, a plant can retain its greenness due to a small sink from a low seed number or a small head (Borrell et al., 2014). This is not a positive trait to increase yield. Thus, when selecting varieties for drought tolerance based on the stay green trait, the need arises to select for both yield and stay green.

Irrigation

Current Status

Fresh water is an incredibly valuable resource that the world depends on every day for sustaining life. Sadly, fresh water is becoming scarce in many parts of the world due to overuse and water pollution (Vörösmarty et al., 2005). Out of all the world's consumption, agriculture constitutes 70 percent of the fresh water use each year, and the resources are dwindling (Xin et al., 2009). This practice cannot be sustained forever because much of the unsustainable overuse of water is from nonrenewable sources of groundwater for irrigation (Vörösmarty et al., 2005).

To bring it closer to home, most of the irrigation in the Central Great Plains in the US depends on the pumping of groundwater. One prominent source of groundwater is the Ogallala aquifer, which has had water level declines since the development of irrigation in the Midwest in the 1950s (Stone et al., 2006). With the diminishing available groundwater, the volume of irrigation water output decreases, and costs increase, requiring more head to pump the water (Stone et al., 2006). This change in cost and productivity will favor limited irrigation compared to full irrigation (Larsen et al., 2002). In many areas, especially in western Kansas, irrigation will be, or already is, limited either through regulations or well capacity, causing farmers to adapt with different irrigation practices. Although crop yields will not be as high as fully irrigated crops, the efficiency of irrigation water applied will be increased. With these adaptations, limited irrigation, whether by choice or not, can be used to increase water use efficiency in crops to produce a high yield with reduced water use (Afshar et al., 2014). It has been suggested that sorghum could be a crop to produce high yields with less water inputs as a result of the dwindling water source (Xin et al., 2009).

Limited Irrigation

Limited irrigation in semi-arid regions will need changes to produce crops that can do well in stressed environments. Grain sorghum is known to do well in stressed environments of both heat and drought and to be more consistent than other crops (Hussein and Alva, 2014). Because sorghum has a high transpiration efficiency, it may be able to be used to produce consistent yields in a crop rotation where irrigation is limited (Xin et al., 2009). Sorghum has been documented to have small grain yield variation across differing levels of irrigation and able to pull moisture from deeper in the soil profile when less irrigation was applied (Klocke et al., 2012a). A greater percentage of the root biomass was lower in the soil profile in non-irrigated sorghum compared to irrigated sorghum (Mayaki et al., 1976). Yields for sorghum are most sensitive to water supply around head emergence for either a yield reduction or yield increase (Stone et al., 2006). So with limited irrigation, it is critical to make sure that sorghum has enough water at this growth stage compared to other growth stages, even though yields respond to other irrigation applications (Maman et al., 2003). Water use in sorghum increases throughout the vegetative stage and peaks from boot stage until after anthesis, and then decreases until maturity (Assefa et al., 2010). Applying water only during reproductive stages to early grain filling has shown merit for limited irrigation and using crop rotations could help use less water to increase longevity of groundwater aquifers (Hergert et al., 1993). This means that the timing of watering will be critical and essential to produce a crop as close to its potential yield as possible using less irrigation water.

With the water content of the Ogallala aquifer decreasing and limited irrigation starting to take place, it will be important to maximize yield by finding the best management practices under all scenarios for sorghum including seeding rates, variety, row spacing, crop rotation, etc. (Baumhardt and Howell, 2006). Resulting from this, a question arises on how to spread out water resources when there is a limit with how much water that can be used to irrigate with. Computer simulators are tools that can be implemented to show previous, current and future crop growth models. A simulator can be helpful in deciding the best fit for different scenarios to determine different options of mixing crops so irrigation water can be allocated (Klocke et al., 2012b) and to understand how different management practices can impact grain yields (Baumhardt and Howell, 2006). No-till and greater residue management can lead to considerably less evaporation which can increase profits (Klocke et al., 2009). Under simulation, grain sorghum on average produces a 7 percent greater yield when row spacing is half of that of traditional 0.76 m row spacing (Baumhardt and Howell, 2006). Simulated grain sorghum yields also showed that to maximize yield for the whole field, it is better to increase irrigation on parts of the field and have complementary dryland areas than to limit irrigate the entire field (Baumhardt et al., 2007).

Efficiency

To be able to understand the economics of balancing available irrigation, yield, and cropping systems, there needs to be sufficient information on crop yield versus water supply (Stone et al., 2006). For farmers to be economically wise with irrigation and costs, they need to be able to maximize the WUE of their cropping system (Stone et al., 2006). As the amount of irrigation increases, WUE decreases (Stewart et al., 1983). Even though yields are not as high as fully irrigated, limited irrigation settings use water more efficiently to have a greater WUE (Stewart et al., 1983). Therefore, the most effective use of irrigation water will be less than maximum ET and would not be at maximum yield (Tolk and Howell, 2003). Since yields plateau as more irrigation water is applied, the most efficient use of water will be less than replacing 100 percent of the water depleted by the crop with similar to slightly less than maximum yields (O'Shaughnessy et al., 2012).

Corn vs. Sorghum

Under optimum conditions, corn is superior for potential yield over sorghum, but in limited water or drought situations, sorghum has qualities that can produce greater yields than corn (Assefa et al., 2014). Although yield potential for corn is greater than that of sorghum, sorghum produces its maximum yield under less evapotranspiration than corn (Assefa et al., 2014). Sorghum yields plateau at a lower rate of irrigation than corn yields (Lamm et al., 2014), and for each unit of irrigation water applied, corn has a greater yield response than sorghum (Klocke and Currie, 2009). Thus, it makes more sense to fully irrigate corn and to apply less irrigation to sorghum (Klocke and Currie, 2009). In southwest Kansas, corn is superior with adequate water supply (irrigation and rainfall), but sorghum is better suited for dryland conditions (Klocke et al., 2014). Although corn is still most profitable with maximum irrigation

(381 mm), crop producers have multiple options with little yield or economic differences when irrigation is limited (127 mm) between corn and sorghum in western Kansas (Schlegel et al., 2016). During years with less than average annual precipitation, grain sorghum could be the more profitable option under limited irrigation in western Kansas (Aiken et al., 2015). In areas or years where corn yields are low because of stress, sorghum tends to have relatively better yields (Staggenborg et al., 2008). Based on yield data from various sites located throughout Nebraska and Kansas, Staggenborg et al. (2008) found that when corn yields are less than 6.4 Mg ha^{-1}, then sorghum typically has a greater yield advantage over corn. Multi-crop rotations and strategies to allocate water under limited irrigation have potential to have similar or greater economic returns (Schlegel et al., 2012). Under limited irrigation, sorghum can be added to a portion of a field along with irrigated corn to limit financial risk and allow for a greater allocation of water to the corn (Klocke et al., 2012a).

Major Knowledge Gaps

Major knowledge gaps are still present for sorghum production research across the Great Plains region. Much of the research and work put into sorghum has been to increase drought tolerance. Sorghum is a more stable crop in environments with limited resources as compared with highly productive and more input-dependent field crops. A recent research study discovered the potential to increase seed number via a mutation in the spikelet to produce three fertile florets instead of only one (Burow et al., 2014). Incorporation of this technology into commercial and productive grain sorghum hybrids is still a step to be taken in order to fully test the potential of this technology into increasing crop yield potential.

Therefore, there still needs to be future work in breeding to increase yields in sorghum. More research needs to be conducted to explore the economics and productivity of different strategies of applying limited irrigation water. Different crop allocations in a field and rotations should be studied to maximize profits and yields and efficiently use the available resources. Future research needs to look at how to maximize sorghum yields under limited irrigation to make it a viable option when corn yields are lower. All of these areas will be helpful to further our understanding and improve sorghum production throughout the world. This study is designed to better understand how different sorghum genotypes respond under different environments to help address some of these issues.

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Chapter 2 - Grain Sorghum Response to Environment

Abstract

Sorghum [*Sorghum bicolor* (L.) Moench] has greater drought resilience than many other crops, producing food under the most stressful environments. Sorghum is a reasonable crop choice for farmers working under limited water supply. The objective of this study was to compare sorghum hybrids differing in yield strategies under varying water supply environments. Yield, biomass, grain harvest index (HI), and yield components (seed number and seed weight) were compared in both rainfed and irrigated situations. Field experiments were established in 2014 and 2015 at Topeka, Scandia, Hutchinson, Garden City, and Tribune, KS. Three sorghum hybrids (Pioneer 85Y40, Pioneer 84G62, and Dekalb 53-67) with different yield potentials at varying water supply were studied. Hybrids 85Y40 and 84G62 tended to have greater yields than hybrid 53-67 when the average environment yield level was greater than 8.5 Mg ha^{-1}. The opposite scenario where hybrid 53-67 had greater yields than the other two hybrids tended to occur for environments yielding less than 8.5 Mg ha^{-1}. In yield group 1 and 2 (>9.5 Mg ha^{-1}, and 8.5-9.5 Mg ha^{-1}, respectively), estimated biomass was similar, but HI was greater for group 1 compared to group 2. Harvest index had a much stronger linear relationship with yield in group 1 (R^2 =0.38) than compared to group 2 (R^2 =0.02) and group 3 (<8.5 Mg ha^{-1}, R^2 =0.13). In group 3 biomass had a stronger linear relationship (R^2 =0.71) with yield than it did in groups 1 and 2 (R^2 =0.27 and 0.12 respectively). Overall, both biomass and HI had linear relationships (R^2 0.38 and 0.10 respectively) with grain yield across all environments, with biomass had an overall stronger relationship than HI. Within the per-panicle grain yield, seed number compared to seed weight (measured in grams per 1000 seeds) had a much stronger relationship with yield (R^2 0.59 and 0.14 respectively). These results suggest the importance of both biomass and HI

with an emphasis of increasing seed numbers when pushing for the maximum yield in high yielding environments, and that biomass production is of utmost importance for yield production in drought prone environments.

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is an important grain crop, ranking fourth among grain crops for area planted behind corn, soybeans, and wheat grain (USDA, 2015). Sorghum is known for its drought resilience and its ability to produce yields in marginal conditions compared to other crops. Since irrigation water is becoming more restricted or limited in many areas of the world (Vörösmarty et al., 2005), crops that are productive and use water more efficiently will be needed. With the predicted population growth (Rakshit et al., 2014) and climate change, sorghum could play a crucial role in food production because of its drought and heat resistant qualities (Emendack et al., 2011).

Several characteristics of sorghum allow it to be better suited for drought and heat stress compared to other crops. Two important traits of sorghum are that it has a very dense root system that can explore as deep as 2.5 meters into the soil profile to extract water, and its leaves have thicker waxy cuticles (Assefa et al., 2010). The ability for osmotic adjustment in sorghum also contributes to its greater drought tolerance (Santamaria et al., 1990). Even though sorghum is known to be more drought resistant than other crops, it can nevertheless be severely affected by drought stress (Assefa et al., 2014).

Improvements in yield as a result of genetics have been much slower for sorghum compared to corn, and about two-thirds of the improvements can be attributed to agronomic practices rather than genetics (Mason et al., 2008). As a result of this slower yield improvement, more acres have shifted from sorghum to planting other crops like corn (Staggenborg et al., 2008). Yield improvements have been the result of both an increase in biomass and HI, although it has been proposed that HI has reached it maximum genetic potential without decreasing overall yield potential (Hammer and Broad, 2003). Improvement in yield potential by increasing total seed numbers rather than increasing seed weight shows promising potential for genetic improvement (Burow et al., 2014).

The main goal of this project was better understand how sorghum reacts to different environments by studying three different hybrids and their underpinning mechanisms for yield formation. Hybrids were planted at different locations with different irrigation levels in order to produce a wide range of environments. Different factors contributing to yield, such as biomass, HI, and yield components (seed weight and number), were quantified to investigate the strategies that these hybrids used to produce yield.

Materials and Methods

Site Description

This experiment was conducted in the state of Kansas from May 2014 to November 2015, for two growing seasons. In parallel with this project, Newell (2016) conducted a complimentary research trials at the same locations studying corn hybrid response to the environment and water supply. Five sites at different Kansas State University research stations across the state were chosen with varying irrigation regimes imposed at each site (Table 2.5) to create different environments. Ten different environments were used in 2014 and nine in 2015 for a total 19 different environments. Table 2.1 shows the different sites with their respective irrigation regimes, average annual precipitation, soil series, and coordinates. Also shown in Table 2.1 are abbreviations used to identify the 19 different environments. Average annual precipitation was obtained from NASA and calculated from 1980 to 2014 (Thornton et al., 2016).

Three different hybrids were used as treatments for each block in a randomized complete block design with four to five replications, resulting in a total of 12 to 15 plots per environment (Table 2.2). At sites that where it was possible to do so, a fifth replication was added in 2015 to sites that were capable of having a fifth replication to statistically increase the power for mean separation. Hybrids were chosen based on an expectation to have different responses to the environment. Pioneer 85Y40, Pioneer 84G62, and Dekalb 53-67 (referred to hereafter as hybrids 1, 2, and 3 respectively) were chosen as the hybrids used for treatments. Pioneer 87P06, hybrid 4, replaced Pioneer 85Y40 in Tribune and Garden City in both growing seasons for their greater adaptation in more arid environments. Seeding rates were determined for each environment by assuming an 85 percent germination rate (as stated on seed bags) to match the targeted plant populations and achieve a feasible yield goal in each environment. Seeds were planted at a depth of 3.81 cm. Each plot was planted 4 rows wide with 0.76 m row spacing for a plot width of 3.04 m. Plots were planted between 9.1 m and 13.7 long (Table 2.2). Sorghum was planted into weed-free plots and was managed throughout the growing season to maintain a weed-free environment.

Fertilizer was applied so that nutrients would be non-limiting in each environment (Table 2.2). Fertility recommendations were based on Kansas State University soil test interpretations and recommendations (Leikam et al., 2003). Soil tests were taken at each site prior to planting to determine how much N, P, and K would be applied.

Measurements

Stand counts were performed shortly after emergence at approximately when the 3rd to 5th leaf collar was visible to estimate the final plant density. An average of four counts was calculated in each plot in lengths of 5.3 meters to determine plant density. Observed plant density was compared to the target plant density and was found to be consistent within each environment (Table 2.3 and Table 2.4).

Biomass measurements were performed approximately at panicle initiation, flowering, hard dough, and physiological maturity (Vanderlip and Reeves, 1972). Aboveground biomass was estimated by cutting five representative plants near the soil surface (10 plants were used for the last biomass measurement and for harvest index at physiological maturity). Plants were weighed fresh and then chopped to obtain a subsample (approximately 0.4 kg) to be dried at 70°C until there was no detectable water loss. Plants at panicle initiation were small enough that whole plants were used for drying and no subsamples were taken. Dry weights of subsamples and plants were measured to determine the dry biomass of the 5 plants, and the average weight of the plants was multiplied by the plant population to determine the aboveground biomass accumulated at the respective growth stage. The plants collected at physiological maturity had the grain threshed before chopping to calculate the HI (procedures for HI explained more in next paragraph). Canopy biomass was obtained by adjusting the biomass to the final combine yields collected at maturity. The accumulated growing degree days were recorded for each biomass sampling date to use for plotting biomass on a growth scale. The growth scale was used since not all the biomass for the different environments were collected at the same physiological growth stage. This growth scale allowed the biomass from different environments to be plotted on a common x-axis to compare across environments. Growing Degree Days (GDD) were calculated by the equation GDD = ((daily max. air temp. + daily min. air temp.)/2) – Base Temp.

(Gerik et al., 2003). The upper limit for maximum air temperature was taken to be 100 degrees F, and the lower limit for minimum air temperature was taken to be 50 degrees F. Base temperature was also taken to be 50 degrees F. If the maximum or minimum daily air temperatures fell outside of the limits, then the limit was substituted for the actual maximum or minimum temperature.

Harvest index measurements were conducted along with the final biomass measurement at physiological maturity. Harvest index was calculated as the ratio of the average grain yield to total aboveground biomass of the sampled plants (i.e., grain yield divided by the total weight of grain, stems, and leaves), both expressed on a dry weight basis. The grain from the 10 plants was threshed with a small grains thresher to separate it from the rest of the plant. The grain portion was then taken to the lab for further analysis. The rest of the plant was chopped and dried to estimate the stems and leaves biomass portion. The total weight of the grain was determined along with the grain moisture, seed number, and seed weight measurements. Grain moisture was recorded by using a Dickie John Grain Moisture Tester (GAC2000 Grain Analysis Computer, Dickey-john Corporation, Auburn, IL). The total weight of the grain was adjusted to zero percent moisture using the actual grain moisture to add to the total aboveground biomass and to calculate the harvest index. Seed weight as the weight of 1000 seeds was calculated by weighing a subsample of approximately 12 grams and using a Seedburo seed counter (Seedburo 801 Count-A-Pack, Seedburo Equipment Company, Chicago, IL) to count the number of seeds. The weight was adjusted to 13 percent moisture and scaled up to the seed weight measurement. These numbers were used to calculate the average seed number of the sampled plants. Seed number was expressed as the number of seeds per panicle and was calculated with the following equation: seed number = (subsample seed number/ subsample seed weight) * (seed weight per panicle).

Leaf chlorophyll concentration was determined at panicle initiation (only in 2014), flowering, and hard dough stages with a SPAD meter (SPAD 502DL Plus Chlorophyll Meter, Spectrum Technologies, Inc., Aurora, IL). Five representative plants were randomly selected for leaf chlorophyll concentration, and the reading was measured in the middle of the flag leaf with the SPAD meter. Canopy temperature was measured at panicle initiation (only in 2014), flowering, and hard dough stages by using a FLIR E40bx infrared thermal camera in 2014 and by using an Omega OS499 Series infrared thermometer in 2015. Canopy temperature was measured in a consistent manner for each time that measurements were conducted by pointing the thermometer at an area of leaves in the upper canopy to obtain the average temperature.

Date of flowering was recorded for each plot when plants were averaging 50 percent of the head in bloom.

The middle two rows of each plot were machine harvested to estimate grain yield when the grain had dried down sufficiently. Harvested area ranged from 14 m^2 to 21 m^2 (Table 2.2). Yields were then adjusted to 13 percent moisture. Environments were grouped into different yield levels based off of the intersection of the grain yield plasticity graph (Figure 2.4) and the environment yield means (Table 2.12) to study trends in the groupings. The environments were grouped into >9.5 Mg ha^{-1}, 8.5-9.5 Mg ha^{-1}, and <8.5 Mg ha^{-1} (group 1, 2, and 3 respectively).

Measurement of Soil Moisture

Soil water content was measured by neutron thermalization with a 503 DR Hydroprobe Moisture Gauge (CPN International, Inc., Martinez, CA) using a count duration of 16 seconds. Access tubes 1.83 m long were installed shortly after emergence in the middle of each plot. The access tubes were type 6061-T6 aluminum tubing with an O.D. of 4.128 cm and a wall thickness of 0.089 cm. Tubes were installed to a depth of 1.68 m deep into the soil profile to measure the soil moisture at depths of 0.152, 0.457, 0.762, 1.067, and 1.372 m. A tractor mounted hydraulic probe (Model GSRTS, Giddings Machine Company, Inc.) was used to make a hole for the tubes with a sampling tube (4.128 cm O.D., Giddings Machine Company, Inc., Windsor, CO) and a drop-hammer was used to drive the tubes to the desired depth. Excess soil was removed from inside the tubes with an auger and the top of the tubes were covered with a PVC cap. Standard counts were measured before and after tube measurements of each reading date on the tailgate of the truck with water removed with a radius of 3.05 m from the neutron probe. A count ratio (CR) was calculated from each tube-depth soil moisture measurement and the mean standard count (CR = measured count/mean standard count). Volumetric water content (θ) was calculated from the factory calibration equation ($\theta = 0.1703*CR - 0.0070$). Soil moisture readings were measured in each tube and depth at emergence, mid-vegetative (panicle initiation), flowering, mid-reproductive (hard dough), and physiological maturity. Precipitation and temperature were recorded from Kansas State University weather stations near each site (http://mesonet.k-state.edu).

Statistical Analyses of Data

Analysis of variance (ANOVA) for each environment was performed using the PROC GLIMMIX procedure in SAS 9.3 (SAS Institute, 2010) to test for treatment effects at a probability value $\alpha = 0.05$. Hybrid was used as fixed factor and replications was used as random effects. In the first approach, the statistical analysis for each variable evaluated was performed for each individual environment. A second ANOVA was performed by combining results from all environments to test for treatment effects. Hybrid, environment, and their interaction were used as fixed effects, and replications were used as random effects. Means of the environments and hybrids were separated by using $\alpha = 0.05$. Date was graphed using GraphPad Prism 5.0

using linear regression and comparing the linear regressions to test whether the lines were significantly different with both slope and intercept. Yield was plotted on the x-axis as the independent variable to analyze the response of the other variables reacted to the growing quality of the environment (indicated by the yield). Nonlinear regression with allosteric sigmoidal curves and a 95 percent confidence interval was used to model the relationship between plot biomass and growing degree days. A one-way ANOVA and Tukey's Multiple Comparison Test was used to test for significant differences between means for the box and whisker plots.

Phenotypic plasticity was used compare yields and harvest index across environments. Plasticity refers to each individual hybrid's reaction to the environment compared to the reaction of the other hybrids to the same environment. The phenotypic plasticity was plotted by using the average of the three hybrids in each environment on the x-axis and by plotting the individual hybrid responses on the y-axis. The points for the different hybrids were analyzed using linear regression to compare the slopes and y-intercepts.

Results and Discussion

Growing Conditions

Precipitation at the five different sites varied over the two years of study (Figure 2.1). Hutchinson and Tribune sites had below average rainfall during the 2015 growing season but the other three sites had either above or similar to average precipitation. Yields for the Hutchinson (7.9 Mg ha^{-}1) and Tribune (8.2 Mg ha^{-1}) dryland environments had the lowest average yields compared (Table 2.7) to the other environments in 2015. For the 2014 growing season, Scandia had below average rainfall for a month long period before flowering, but an increase in rainfall after flowering resulted in this site receiving similar to average precipitation by the end of the growing season. Dryland yields did not decrease as much as expected from this dry period due to a malfunction in the irrigation software resulting in an application of irrigation water on July 11 (Table 2.6). The other sites had similar to average rainfall amounts during the growing season with Garden City having above average rainfall. Average yields were lowest at Garden City (3.6 Mg ha^{-1}), Hutchinson (4.2 Mg ha^{-1}), and Tribune (6.6 Mg ha^{-1}) dryland environments for the 2014 growing season (Table 2.6). Daily recorded temperatures and average daily temperatures are displayed with the flowering date for each site for both growing seasons in Figure 2.2.

Yield, Biomass, and Yield Components

In high yielding environments (8.5 Mg ha^{-1} and greater) hybrids 1 and 2 tended to have greater average yields (Table 2.6 and Table 2.7) compared to hybrids 3 and 4, but the opposite was true to for lower yielding environments (less than 8.5 Mg ha^{-1}). A significant interaction between the hybrid and environment occurred with no difference in hybrid mean yield across all environments (Table 2.10). Significant differences did show up within environments though. For TOPIR14 (Table 2.1 for abbreviations), hybrid 1 had a greater yield than hybrid 3, and hybrid 2 had statistically similar yields to hybrid 1 and 3. Hybrid 2 had statistically (p-value $<$ 0.05) greater yields in SCAD14 compared to hybrids 1 and 3. One exception occurred at HTC6614 where hybrid 2 had a greater yield than hybrid 1, but hybrid 3 had similar yield to both hybrid 1 and 2. Yield differences in lower yielding environments were more difficult to detect because there was more variability among replications. Due to lodging and its different effect on hybrids differently in HTCD14, hybrid 3 had a greater yield than hybrids 2 and 1, and hybrid 2 had a greater yield than hybrid 1. Looking to biomass and harvest index, which were measured before lodging had occurred, less of a difference in estimated grain yield was evident, though hybrid ranking stayed the same. No other environments had statistically different grain yields between the hybrids, but hybrid 3 and 4 consistently produced greater yields than hybrids 1 and 2 in lower yielding environments with few exceptions. Yields for HTCIR14 were much less than the expected yields due to lodging of all hybrids from a rain storm and wind before harvesting. All three hybrids were affected equally by the lodging, and no statistical differences were found in this environment. Although the average yields were low in this environment, the hybrids would have had the same trend as the higher yielding environments. In both Topeka environments in 2015, bird damage caused pronounced yield reductions (visual estimation of around 10 percent loss) to all three hybrids equally.

Regardless of the environment, hybrids 1 and 2 typically had a greater harvest index (HI) than hybrid 3 (Table 2.6 and Table 2.7) with a significant interaction with the environment (Table 2.10). All statistical differences showed up in environments from the 2015 growing season. Since the sampling methods were improved from the 2014 season (10 plants were sampled from each plot during the 2015 season instead of 5 for the 2014 season), the HI shows more statistical differences from the 2015 growing season than the 2014. Though there may be actual HI differences from the other environments (especially in 2014), none show any statistical significance. Harvest indices for hybrids 1 and 2 were greater than hybrid 3 in three environments (HTCIR15, TOPD14, and TOPIR15). Hybrid 1 had a greater HI than both hybrids 2 and 3 in SCAD15. In HTCD15 hybrid 1 had a greater HI than hybrid 3, hybrid 2 did not differ statistically on the HI as relative to hybrids 1 and 3. Most of the values from this study are similar to the range of HI values of 0.3 to 0.5 reported by Steduto et al. (2012) with the larger values reaching the HI ceiling of 0.55 proposed by Tolk and Howell (2009).

Differences in biomass between hybrids were minimal and variable among the different environments (Table 2.6 and Table 2.7). Due to lodging of different extent between hybrids, HTCD14 shows a difference in biomass at maturity, although no difference can be assumed since individual plant weights multiplied by plant populations show no significant difference. There were no statistical differences in any other environment for biomass at maturity. The highest biomass estimation (SCAD14 with biomass of 2574 g m^{-2} and a grain yield of 9.4 Mg ha^{-1}) is similar to a study in Australia that had 2489 g m^{-2} biomass and a corresponding grain yield of 9.2 Mg ha^{-1} (van Oosterom et al., 2010).

Seed number per panicle was generally greater for hybrids 1 and 2 compared to hybrid 3 across all environments (Table 2.13) with no significant interaction with the environment (Table 2.10). Statistical differences showed up in TOPIR14 and TOPD15 (Table 2.6 and Table 2.7). In TOPIR14, hybrid 1 had a greater seed number than both hybrid 2 and 3. Hybrid 2 had a greater seed number compared to both hybrid 1 and 3 in TOPD15.

Two environments had significant differences in seed weight between the hybrids (Table 2.6 and Table 2.7). Hybrid 3 had a greater seed weight than both hybrid 1 and 2 in HTC6614. In HTCIR15, hybrid 2 had a greater seed weight than hybrid 3, and hybrid 1 did not differ statistically on seed weight to both hybrids 2 and 3. Hybrids 2 and 3 had a greater seed weight across all environments with no significant interaction with the environment (Table 2.13).

In Season Measurements

Leaf chlorophyll content measured with the SPAD meter showed a trend for hybrids 1 and 2 to have greater SPAD values than hybrid 3 regardless of the environment (Table 2.14). A greater percentage of SPAD measurements showed differences at the flowering stage followed by the panicle initiation stage measurement time (Table 2.8 and Table 2.9). The hard dough stage had the lowest percentage of differences compared to the other two reading times. During the panicle initiation stage, hybrid 1 and 2 were similar but had greater SPAD values as relative to hybrid 3 at HTCIR14. Hybrid 1 had a greater SPAD reading than hybrid 3 with hybrid 2 being similar to both hybrids at SCAIR14 and HTCD14 environments. During the flowering stage, hybrids 1 and 2 had greater SPAD readings in six environments: HTCD15, HTCIR15, SCAD15, TOPD14, TOPD15, and TOPIR15. Two environments (HTCD14 and SCAIR15) had SPAD values following the order from high to low: hybrid 1>hybrid 2>hybrid 3. Measurements during the hard dough stage had two environments (SCAIR14 and HTCD15) where hybrids 1 and 2 had a greater SPAD reading than hybrid 3. One environment (HTC6614) showed hybrid 1 having a greater SPAD reading than hybrid 3, whereas hybrid 2 was similar to both hybrids.

Even though there were many differences in measured SPAD values between hybrids, the relationship between SPAD readings and yield was significant, but not very strong with low coefficient of determination values (Figure 2.3).

There were no significant differences in canopy temperature among hybrids at panicle initiation or hard dough stages at all environments (Table 2.8 and Table 2.9). Differences between hybrids were minimal with no consistency in different environments. At flowering, hybrids 1 and 3 had significantly lower canopy temperature than hybrid 2 at HTCD15. In SCAIR14 environment, hybrid 1 had a lower canopy temperature than both hybrids 2 and 3.

Comparing length of the vegetative-period, hybrid 1 typically had a shorter period of days to flowering followed by hybrids 2 and then 3 (Table 2.8 and Table 2.9). Five environments had no difference between hybrids in their days to flowering. Four environments (HTC6614, HTCD14, HTCIR14, and TOPD15) had a significant difference with hybrid 1 having shorter days to flowering than hybrids 2 and 3 with hybrid 2 having a shorter period than hybrid 3. Other environments (HTCHIR15, SCAD15, SCAIR15, TOPD14, TOPIR14, and TOPIR15) show hybrid 1 having a shorter days to flowering period than both hybrids 2 and 3, which were both similar. These results of relative days to flowering agree with the hybrid descriptions on their respective company websites with days to flowering at 70 and 72 for hybrids 1 and 2 respectively (www.pioneer.com) and 72 days for hybrid 3 (www.agseedselect.com).

Soil Water Content

The change in soil water content from planting to harvest was not consistent throughout the environments. Hybrids 2 and 3 had a greater reduction in the soil moisture content than hybrid 1 in HTC5015 and had a greater reduction than hybrid 4 in TRID14. Hybrid 2 had a greater reduction in soil moisture content compared to hybrid 1 in SCAD15, but hybrid 3 did not differ statistically from both hybrids 1 and 2. More information on soil water content is presented and discussed in Appendix A-Soil Volumetric Water Content Data.

Hybrid Plasticity and Linear Relationships

Grain yields of the individual hybrids for each environment were regressed versus the mean yield for all three hybrids within each environment ("phenotypic plasticity") obtaining a linear regression (Figure 2.4). Hybrids 1 and 2 had similar regression lines (F test, Mead et al., 1993) but differed from hybrid 3. As mean environmental yield increased, yields for hybrids 1 and 2 increased at a greater rate than for hybrids 3 and 4. The intersection point for hybrids 1 and 3 was at a yield of 8.4 Mg ha^{-1} whereas the regression line for hybrid 3 intersected hybrid 2 at a yield of 8.2 Mg ha^{-1}. Therefore, hybrids 1 and 2 would have a yield advantage over hybrid 3 in environments yielding greater than >8.4 Mg ha^{-1}, but hybrid 3 is expected to outyield hybrids 1 and 2 in environments yielding less <8 Mg ha^{-1}. The hybrid and environment interaction is significant (Table 2.10) indicating that the hybrids reacted differently to the environments in which they were grown.

Environments were divided into three yield levels of < 8.5 Mg ha^{-1}, 8.5 – 9.5 Mg ha^{-1}, and > 9.5 Mg ha^{-1} (yield group 3, 2, and 1 respectively) to see what factors contributed most to yield in each set of environments. Environments were divided into these groups by distinguishing statistical yield differences among environments (Table 2.12) and by using the intersection from the grain yield hybrid plasticity (Figure 2.4). Biomass and HI were regressed with yield data from each plot (Figure 2.5 and Figure 2.6 respectively) to better understand their contributions to yield. Although biomass and HI were both positively correlated with yield, biomass was more strongly correlated with yield than HI. Further investigation of both biomass and HI within the yield groupings revealed that biomass was much more strongly correlated with yield in the yield group 3 than in the other two yield groupings (Figure 2.7 and Figure 2.8) confirming Blum's argument that biomass production should be maximized in drought conditions as well as high yielding environments (Blum, 2009). This is also similar to findings by Narayanan et al. (2013) who showed that increase in drought tolerance was caused by an increase in biomass rather than a decrease in water use. The opposite was true for HI, which was correlated more strongly with yield group 1 than in the other two yield groupings (Figure 2.7 and Figure 2.8).

Graphing phenotypic plasticity for biomass and harvest index showed that the hybrids had statistically similar biomass production throughout the range of environments (Figure 2.9), but that HI had significantly different slopes (Figure 2.10). The HI slopes for hybrid 1 and 2 were similar whereas hybrid 3 had a less steep slope. Therefore, the difference in yields in the higher yielding environments by hybrids 1 and 2 resulted not from an increase in biomass over hybrid 3, but from an increase in HI. The hybrids combined in the group 1 did not produce statistically greater biomass than yield group 2 (Figure 2.13), but had greater HI values (Figure

2.14). This study shows the need for biomass and HI to be maximized for greatest yields just as Hammer and Broad (2003) found that the higher yields in their study were achieved by maximizing both biomass and HI.

Looking further into HI and what makes up the grain portion of the plant, seed number and seed weight (g (1000 grains)$^{-1}$) were regressed with the per-panicle grain yield from the HI sample plants (Figure 2.15 and Figure 2.16). Both seed number and seed weight exhibited significant positive relationships with per panicle-grain yield. This finding is in agreement with the results of Maman et al. (2004), who also found that both seed number and seed weight were correlated to yield. Between the two factors that make up the per-panicle yield, seed number had a stronger linear relationship (R^2 =0.59) as compared to the seed weight (R^2 =0.14) with per-panicle yield. This supports the initiatives of Burow et al. (2014) to increase grain yield by increasing seed number by a mutation in number of fertile florets.

Biomass accumulation throughout the growing season was plotted against sorghum growing degree days to eliminate differences between stages of biomass sampling (Gerik et al., 2003). Within each yield group, hybrid biomass did not differ with a 95 percent confidence interval (Figure 2.11). Therefore, one curve can represent the biomass accumulation in each yield grouping. A comparison of biomass accumulation between the different yield groupings revealed that accumulation curves were different (Figure 2.12). At physiological maturity, total plant biomass for yield group 3 was less than that for yield groups 1 and 2 (Figure 2.13). Total plant biomass was comparable for both groups 1 and 2. Although biomass was similar for yield groups 1 and 2, HI was highest for the yield group 1 (Figure 2.14).

Conclusions

Hybrids 1 and 2 consistently had greater yields than hybrid 3 in environments that had an average yield of 8.5 Mg ha^{-1} or more. This is shown by the statistically significant interaction of hybrid and environment and the statistically different slopes displayed in the phenotypic plasticity yield graph. The opposite was found for environments having average yield less than 8.5 Mg ha^{-1}, where hybrid 3 tended to have greater yields than both hybrid 1 and 2. Although there were no statistical differences between yields in the lower yielding environments of this study due to variability, this trend is confirmed by the phenotypic plasticity graph. Biomass for all three hybrids showed no statistical differences, but HI for hybrids 1 and 2 were consistently greater than hybrid 3.

Yield increase was significantly correlated with both biomass and HI, but overall biomass appeared to be of greater importance than HI as a yield determining factor, primarily in yield group 3 (<8.5 Mg ha^{-1}). Grain HI portrayed a stronger linear relationship with sorghum yields in yield group 1 (>9.5 Mg ha^{-1}). At maturity, comparable biomass was documented for yield groups 1 and 2, but HI for yield group 1 was greater than that of the other yield groups.

Within the grain portion of the plant, seed number had a much stronger relationship to yield than seed weight. Therefore, since hybrids 1 and 2 had greater HI at high-yielding environments, they generally had greater yields than hybrid 3 above the intersection of the yield phenotypic plasticity graph (~8.5 Mg ha^{-1}). By contrast, hybrid 3 tended to have greater yields below the intersection (i.e., in low-yielding environments), with a strong relationship between biomass and yield.

This study supports other studies that have examined increasing yield in grain sorghum, but it also shows a need for future research to be done to improve grain production. Since there were only three hybrids in this study, more hybrids could be studied under different environments to see if the trends are true for other hybrids. Management practices such as plant density and row spacing should be combined with this study to try to push the limits of grain sorghum yield. It seems that more research has been done on sorghum's drought tolerance rather than on greater maximum yield potential. Future work needs to be done increase the genetic yield potential of sorghum to have a greater response as more water is supplied. Even though this study was not designed to analyze the effect of irrigation in a site, more research should be done to examine sorghum water use and when yield no longer increases with additional water input.

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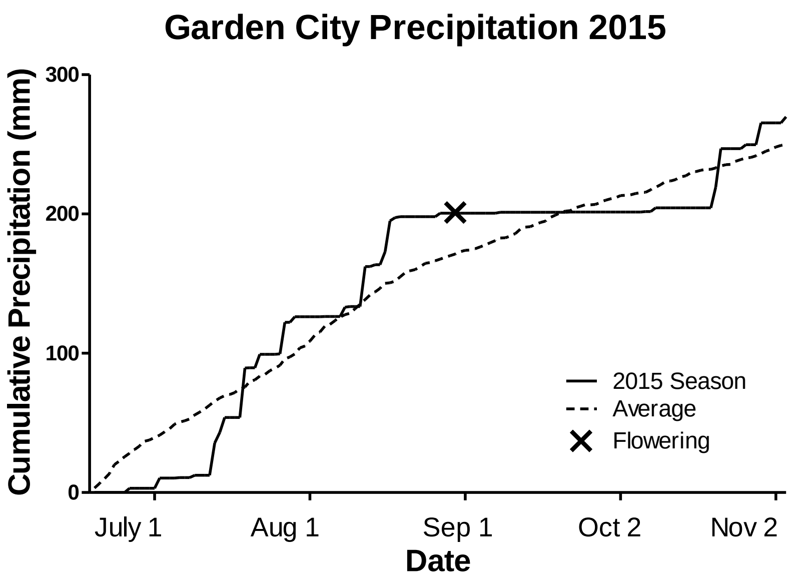
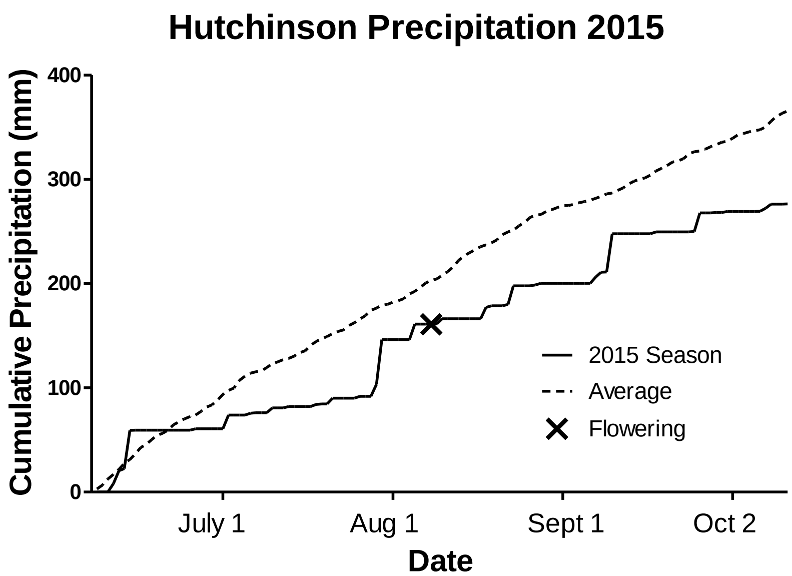
Tables and Figures


Garden City Precipitation 2015
Cumulative Precipitation (mm)
300
200
100
0
July 1
Aug 1
Sep 1
Oct 2
Nov 2
Date
2015 Season
Average
Flowering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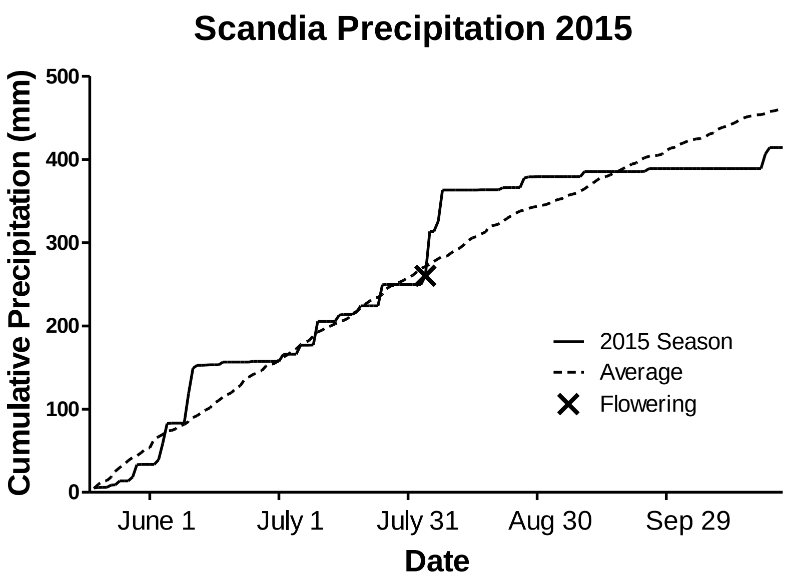
200
100
0
July 1
Aug 1
Sept 1
Oct 2
Date
2015 Season
Average
Flowering


Scandia Precipitation 2015
Cumulative Precipitation (mm)
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200
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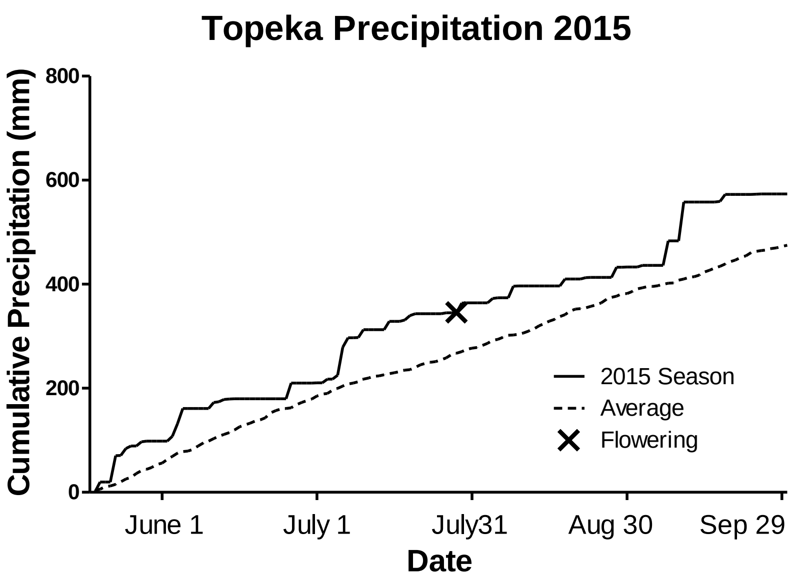
0
June 1
July 1
July 31
Aug 30
Sep 29
Date
2015 Season
Average
Flowering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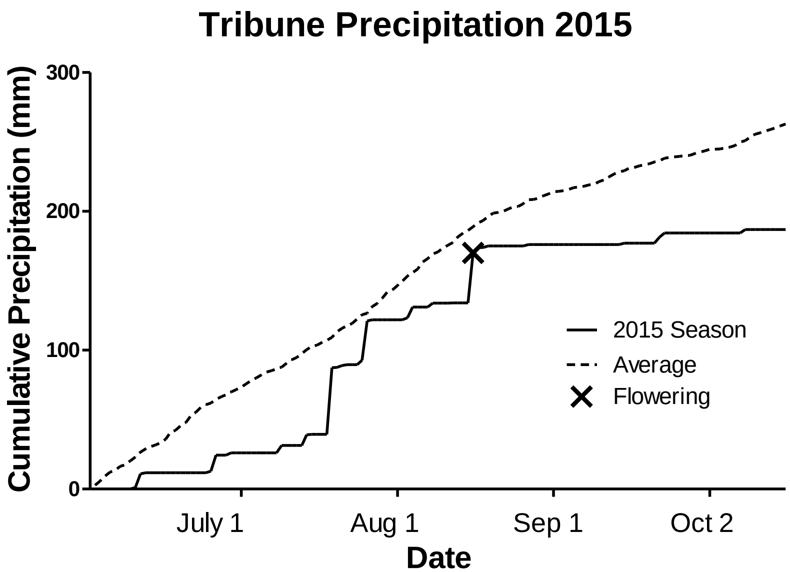
400
200
0
June 1
July 1
July31
Aug 30
Sep 29
Date
2015 Season
Average
Flowering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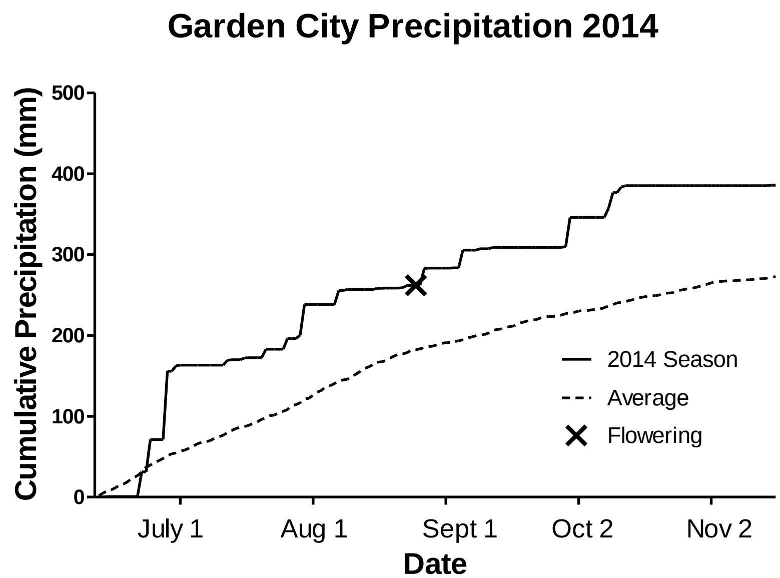
Oct 2
Date
2015 Season
Average
Flowering


Garden City Precipitation 2014
Cumulative Precipitation (mm)
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400
300
200
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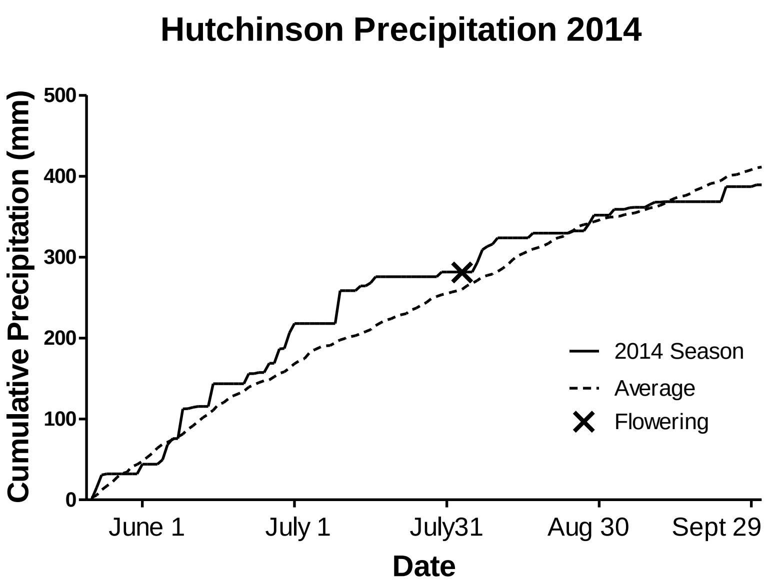
July 1
Aug 1
Sept 1
Oct 2
Nov 2
Date
2014 Season
Average
Flowering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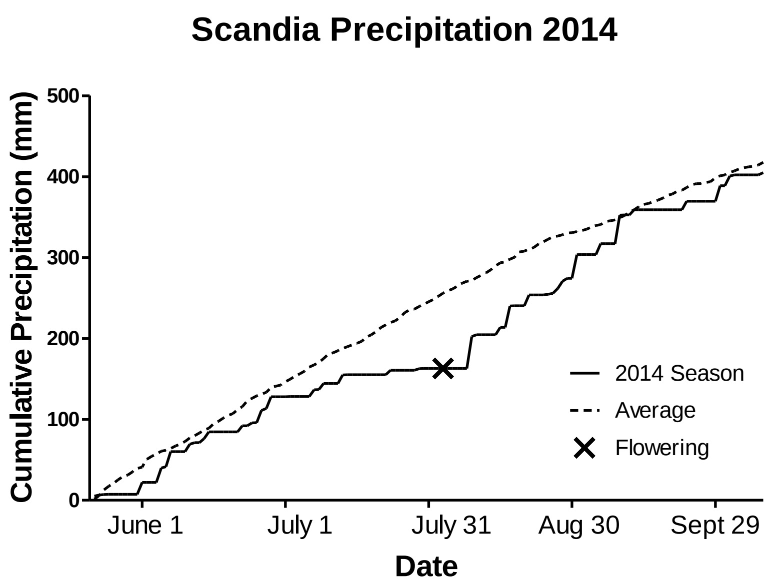
Date
2014 Season
Average
Flowering


Scandia Precipitation 2014
Cumulative Precipitation (mm)
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400
300
200
100
0
June 1
July 1
July 31
Aug 30
Sept 29
Date
2014 Season
Average
Flowering

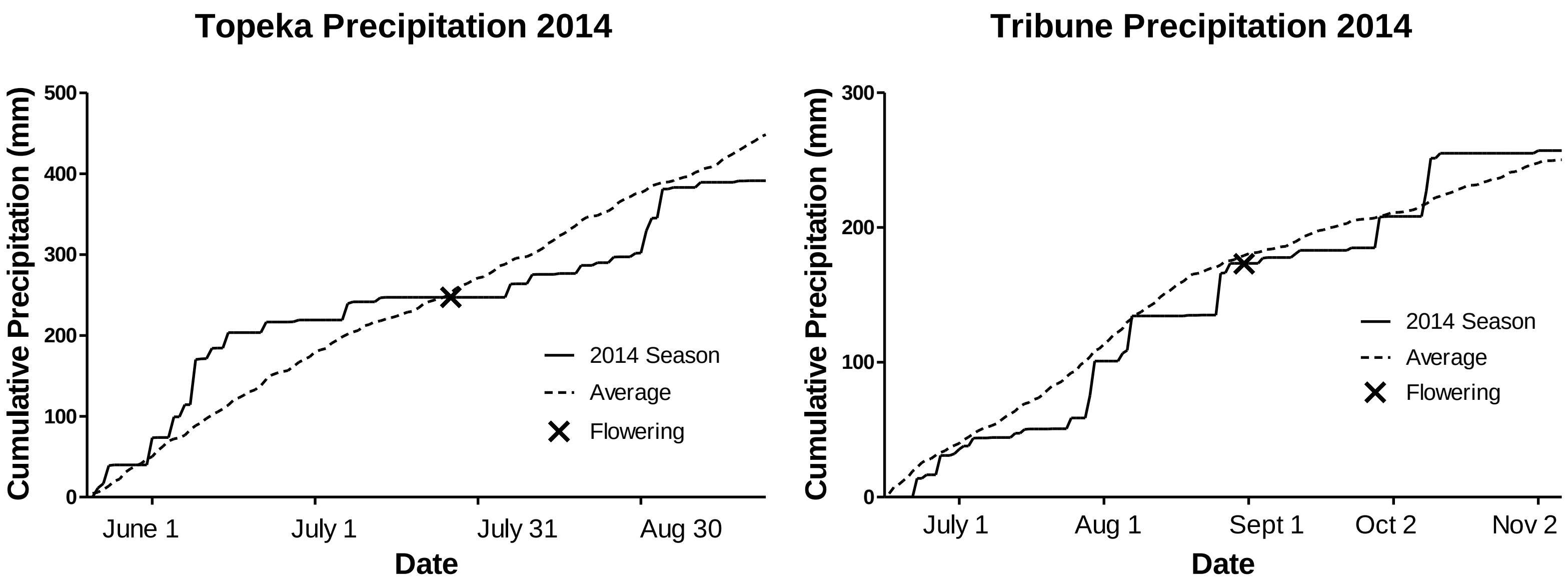
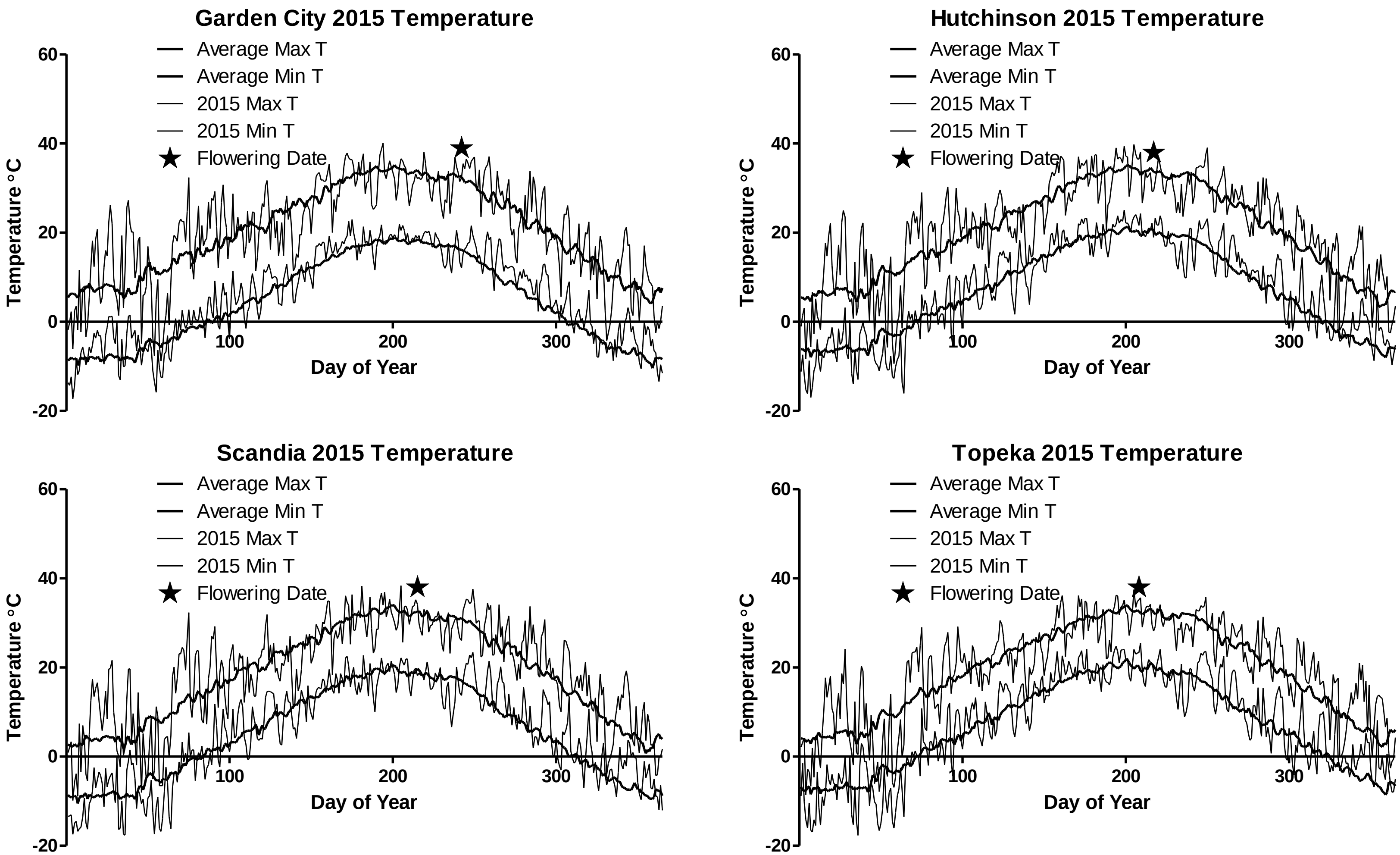


Figure 2.1 Cumulative Precipitation and Average Precipitation with Flowering Date throughout the 2015 and 2014 Growing Seasons.


Garden City 2015 Temperature
Hutchinson 2015 Temperature
Scandia 2015 Temperature
Topeka 2015 Temperature
Average Max T
Average Min T
2015 Max T
2015 Min T
Flowering Date
Temperature °C
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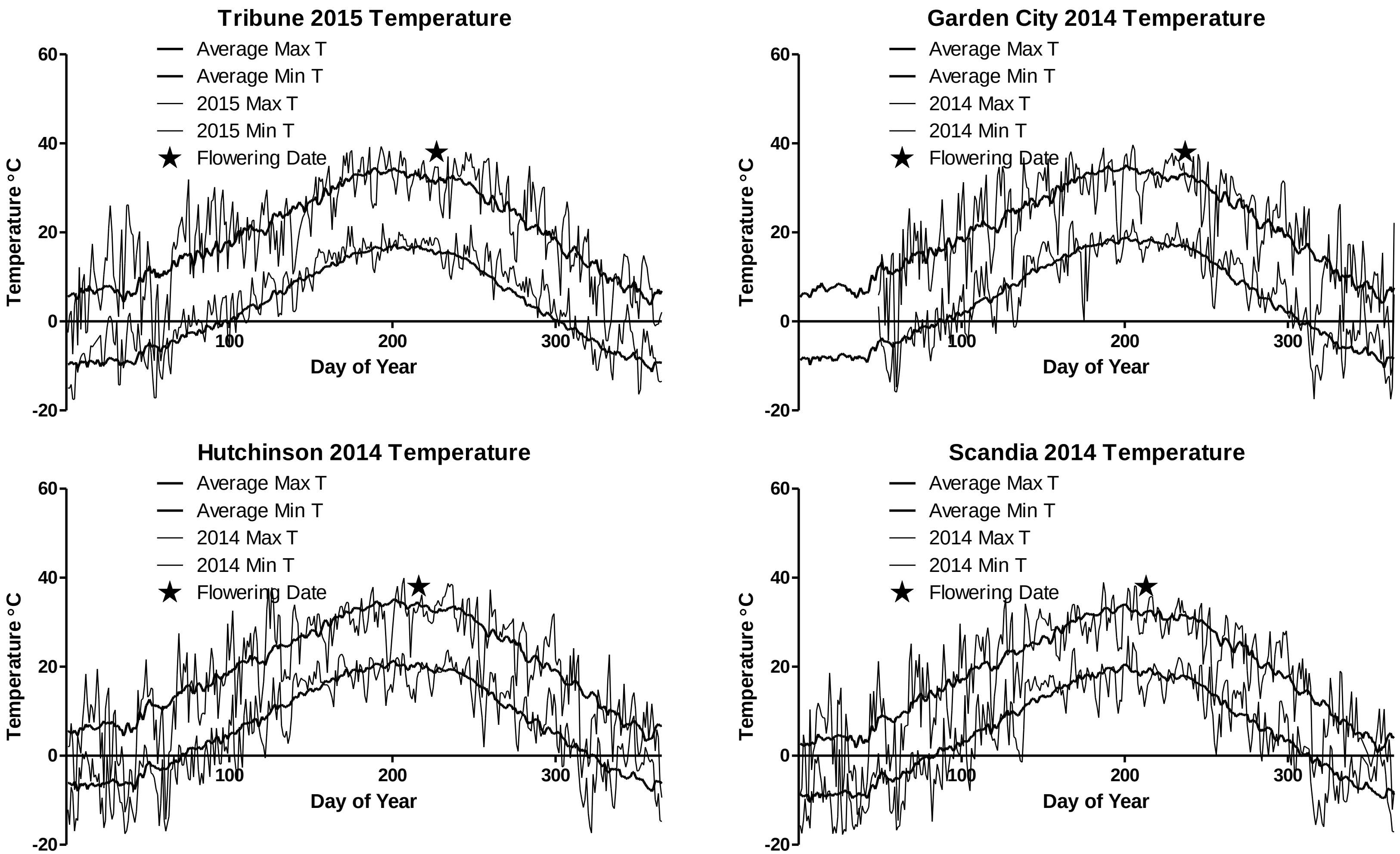
0
-20
100
200
300


Tribune 2015 Temperature
Average Max T
Average Min T
2015 Max T
2015 Min T
Flowering Date
Temperature °C
Day of Year
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40
20
0
-20
100
200
300
Garden City 2014 Temperature
Average Max T
Average Min T
2014 Max T
2014 Min T
Flowering Date
Temperature °C
Day of Year
Hutchinson 2014 Temperature
Average Max T
Average Min T
2014 Max T
2014 Min T
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Flowering Date
Temperature °C
Day of Year

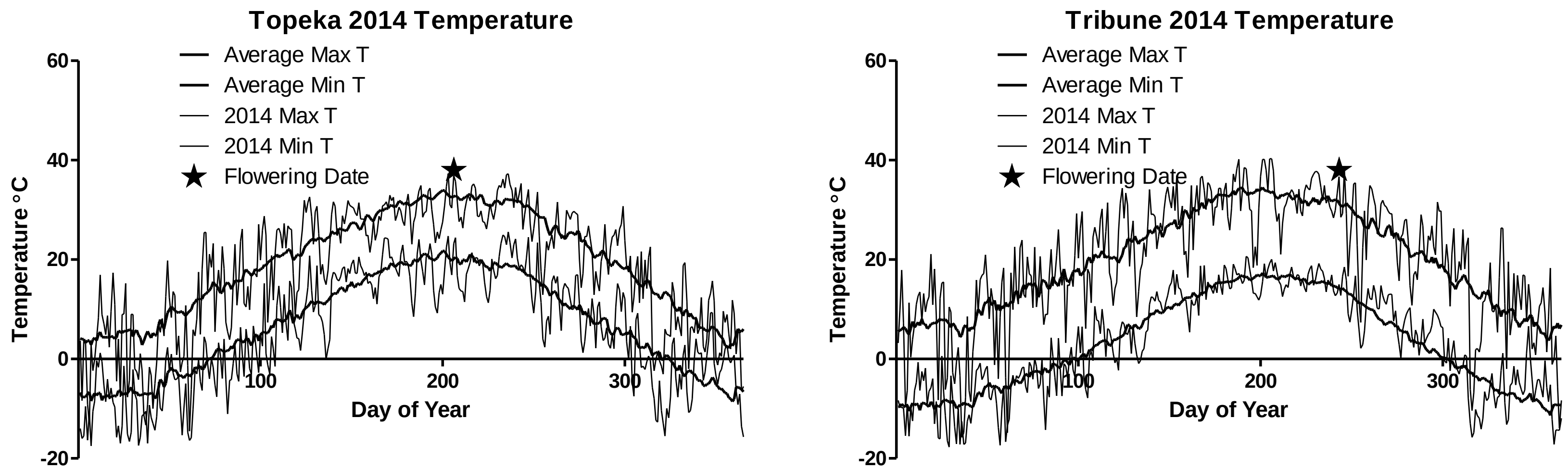
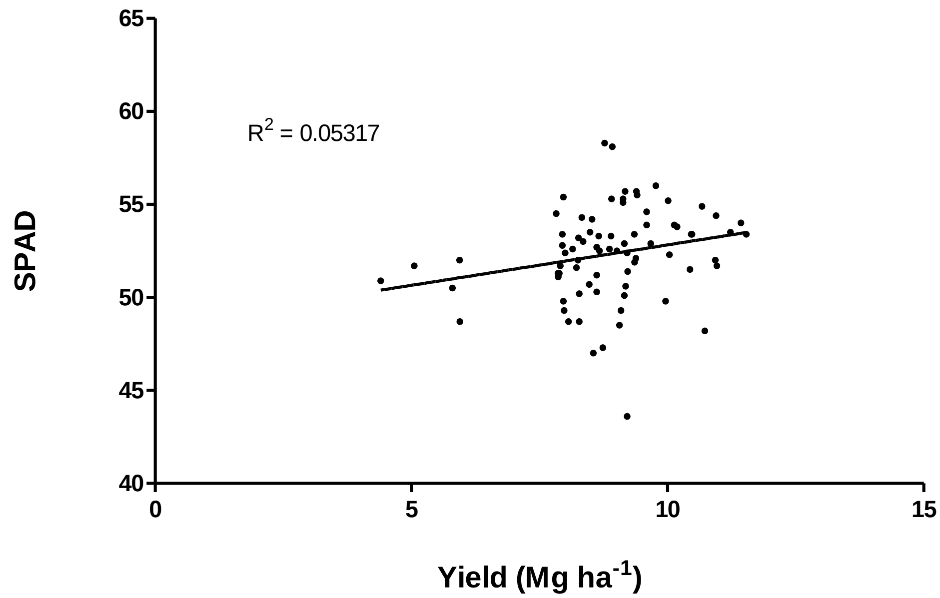
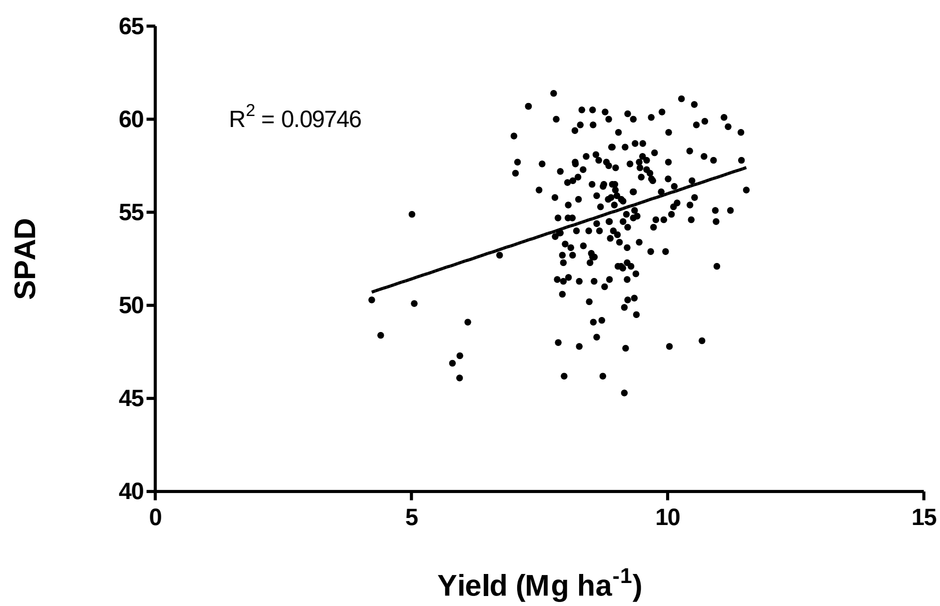


Figure 2.2 Daily Actual and Average Temperatures with Flowering Date for all Sites for the 2015 and 2014 Growing Season.

SPAD Mid-Vegetative



SPAD Flowering



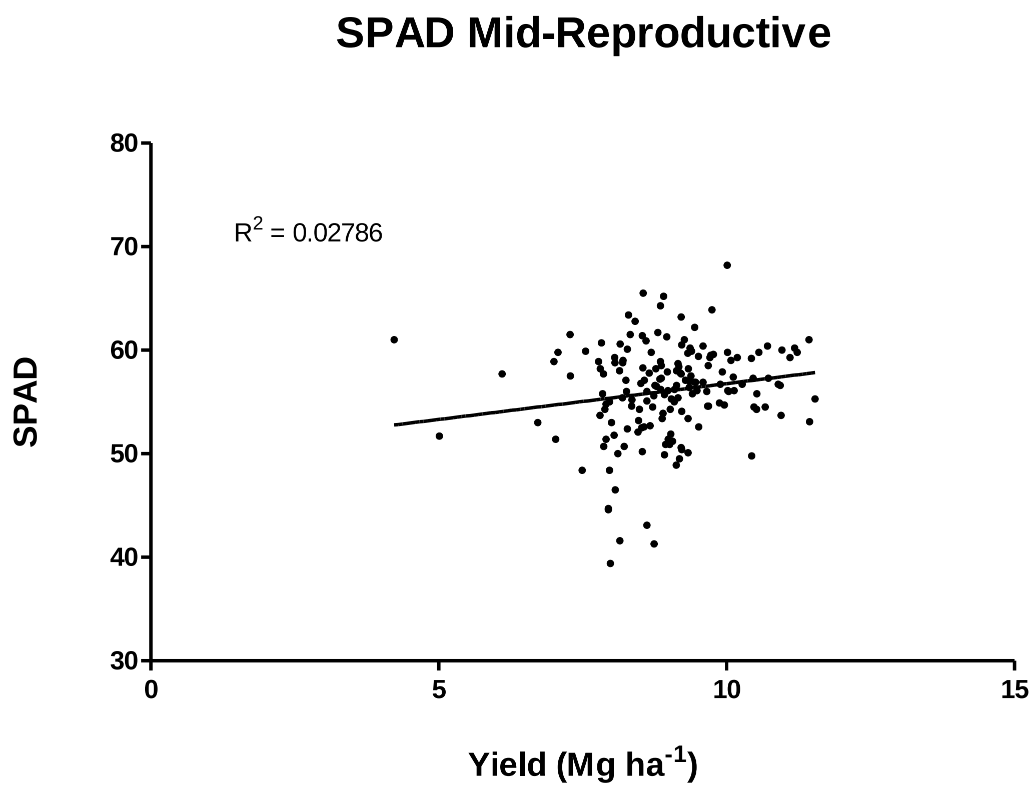


Figure 2.3 SPAD Meter Measurements Regression with Yield from all Plots in all Environments for the 2014 and 2015 Growing Seasons.

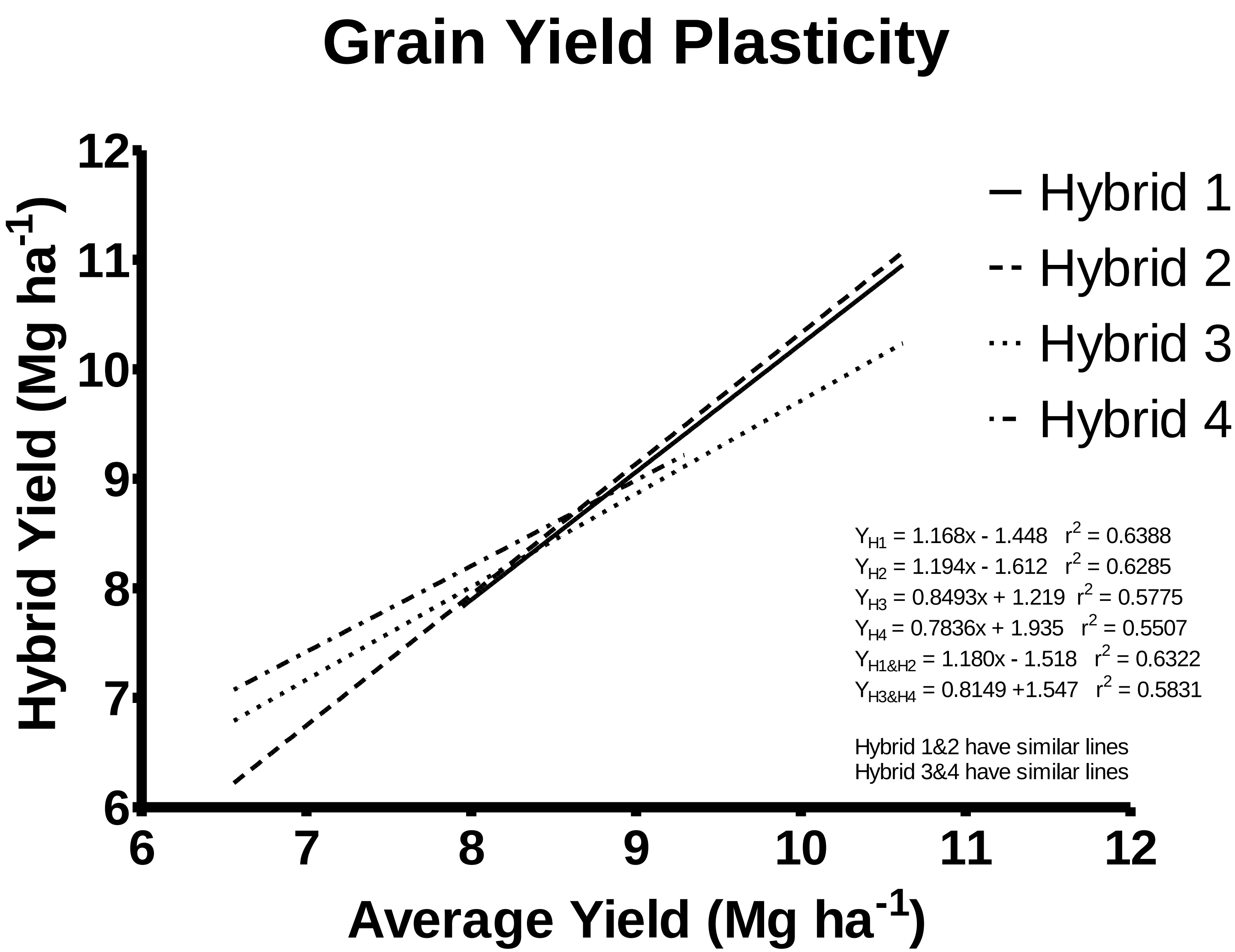


Figure 2.4 Grain Yield Plasticity with the Average Yield of the Three Hybrids on the x-axis and the Individual Hybrid Yield Plotted on the y-axis for all Environments for 2014 and 2015.

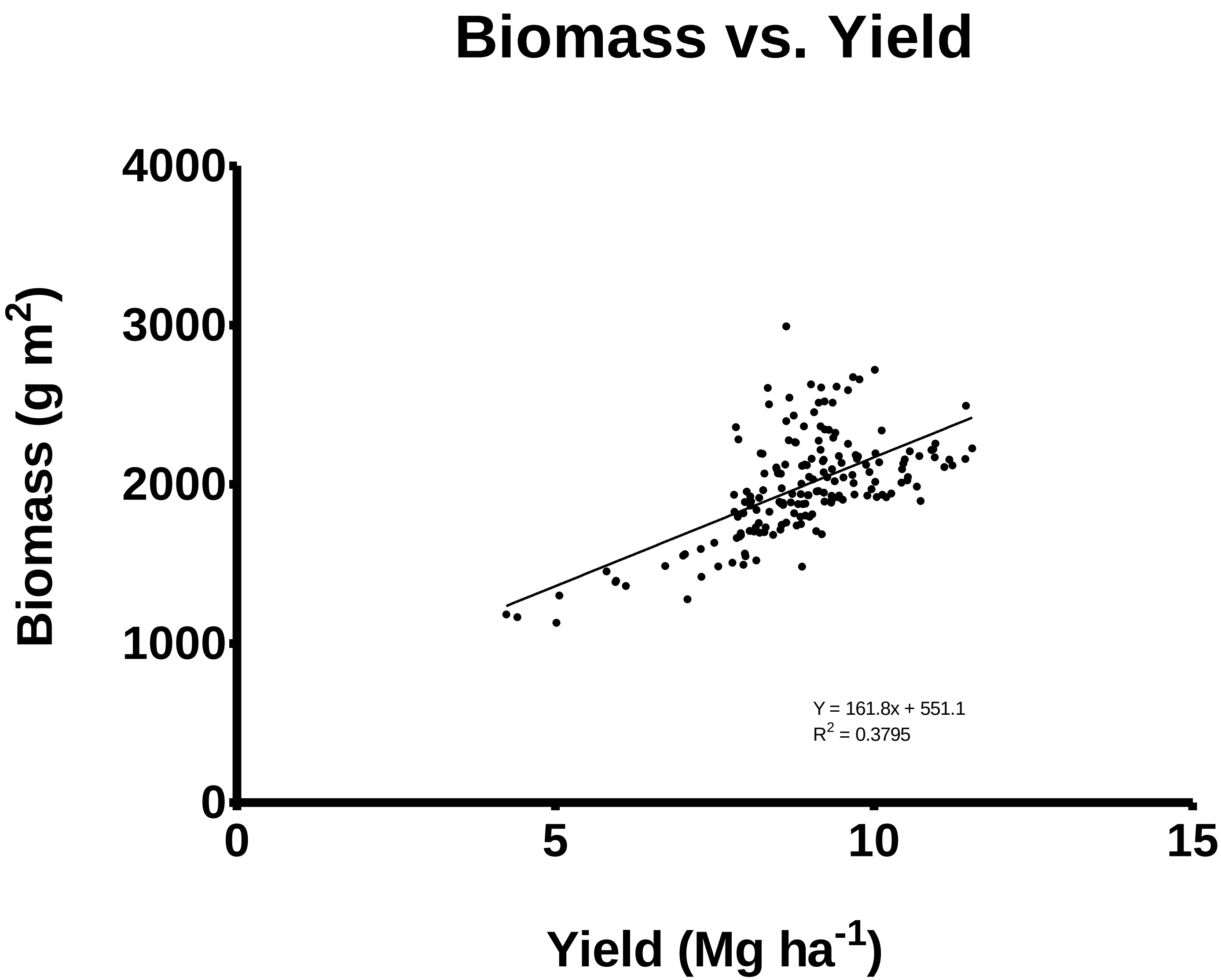


Figure 2.5 Biomass vs. Yield Regression Line for all Plots in all Environments for 2014 and 2015.

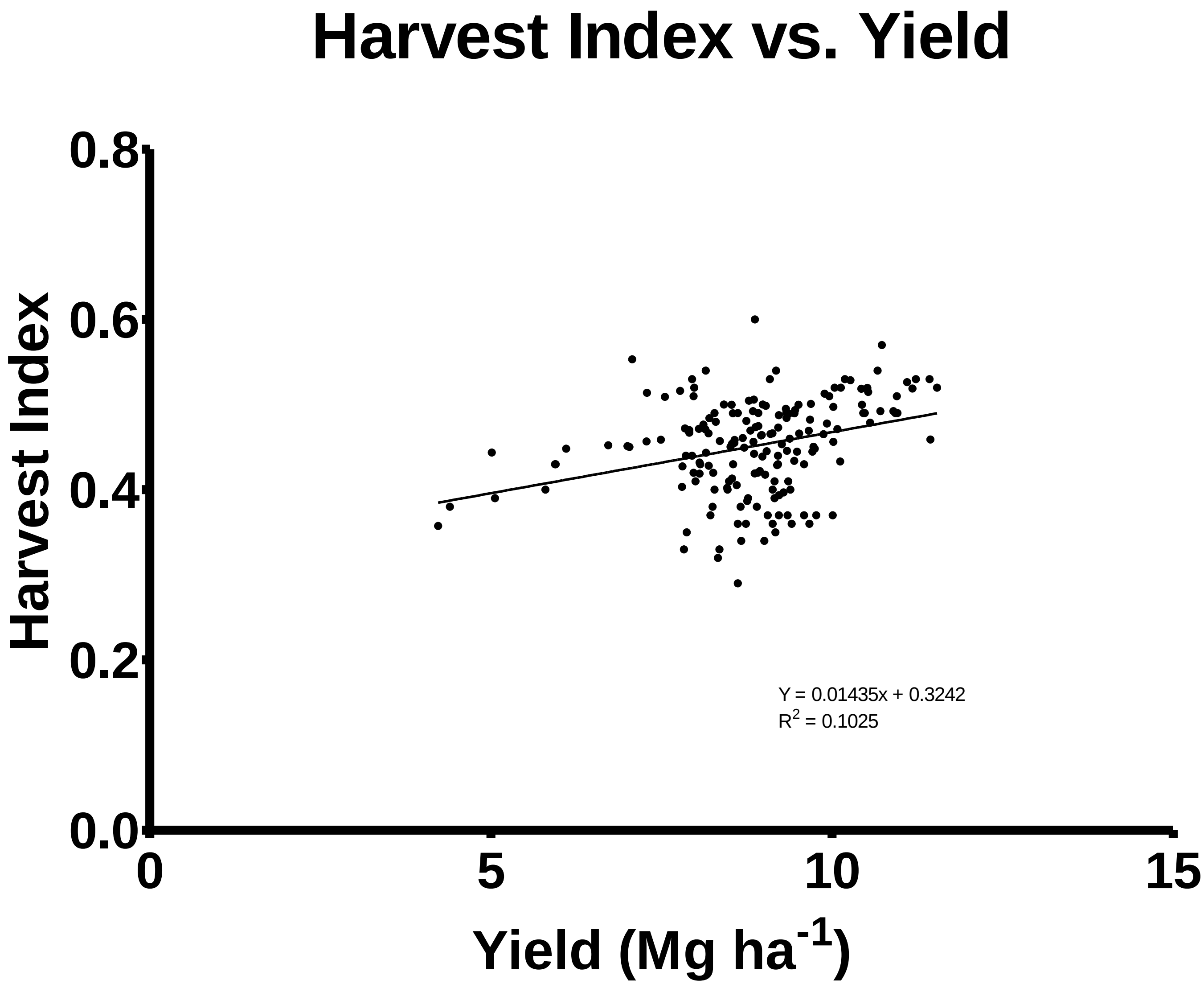


Figure 2.6 Harvest Index vs. Yield Regression Line for all Plots in all Environments for 2014 and 2015.

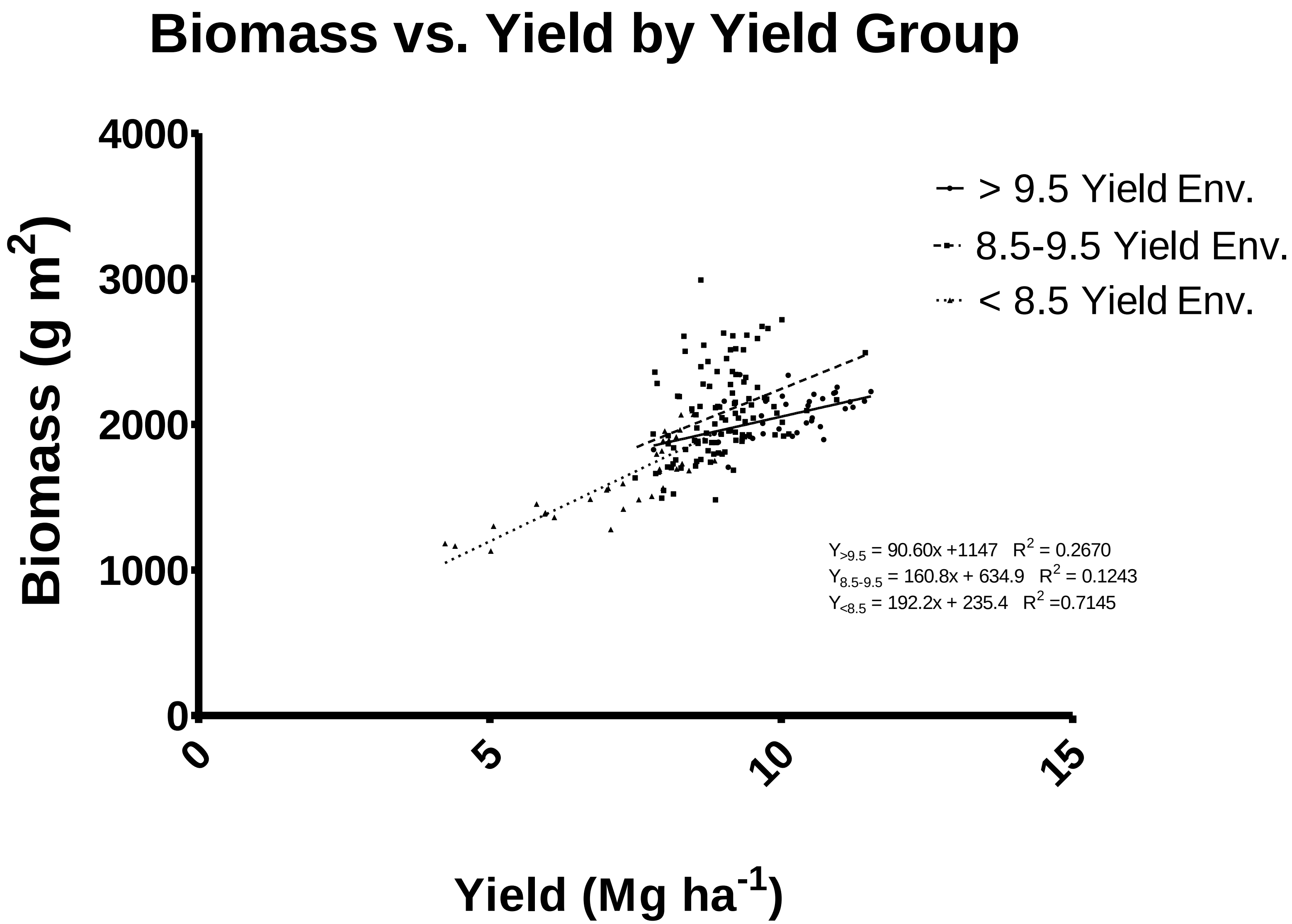


Figure 2.7 Biomass vs. Yield for all Plots in all Environments for 2014 and 2015 Separated by the Yield Group.

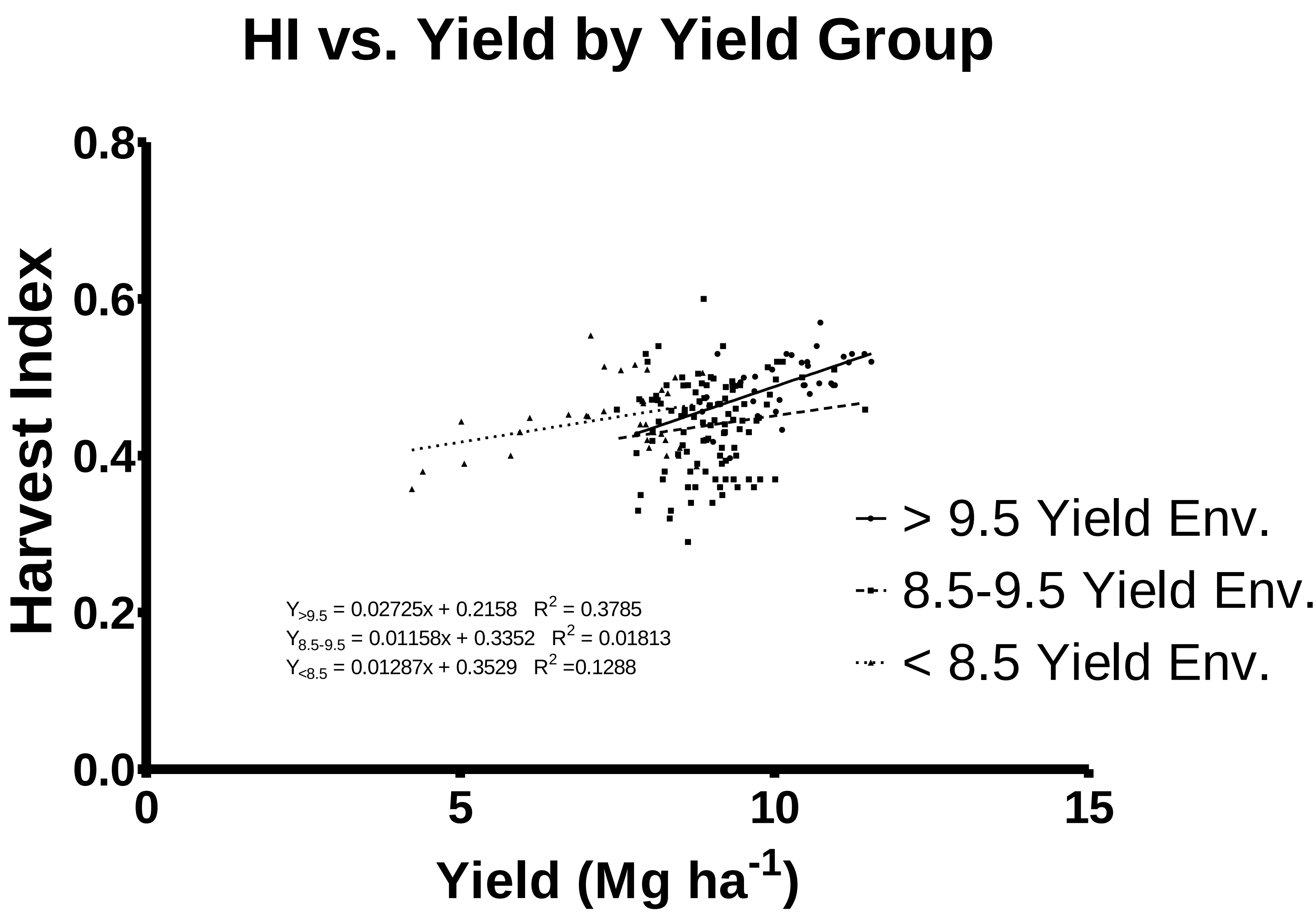


Figure 2.8 Harvest Index vs. Yield for all Plots in all Environments for 2014 and 2015 Separated by the Yield Group.

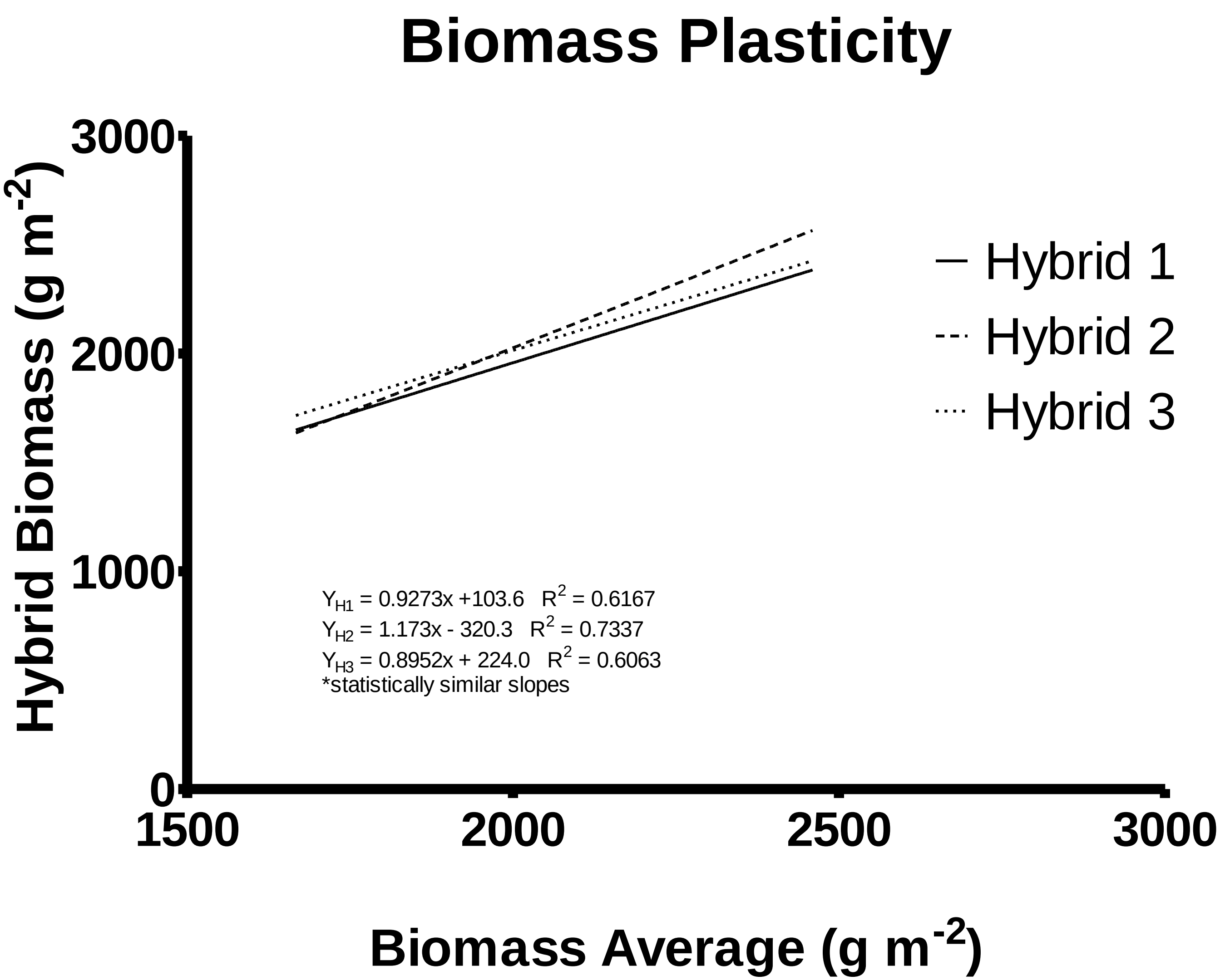


Figure 2.9 Biomass Phenotypic Plasticity with the Average Biomass of the Three Hybrids on the x-axis and the Individual Hybrid Biomass Plotted on the y-axis for all Environments for 2014 and 2015.

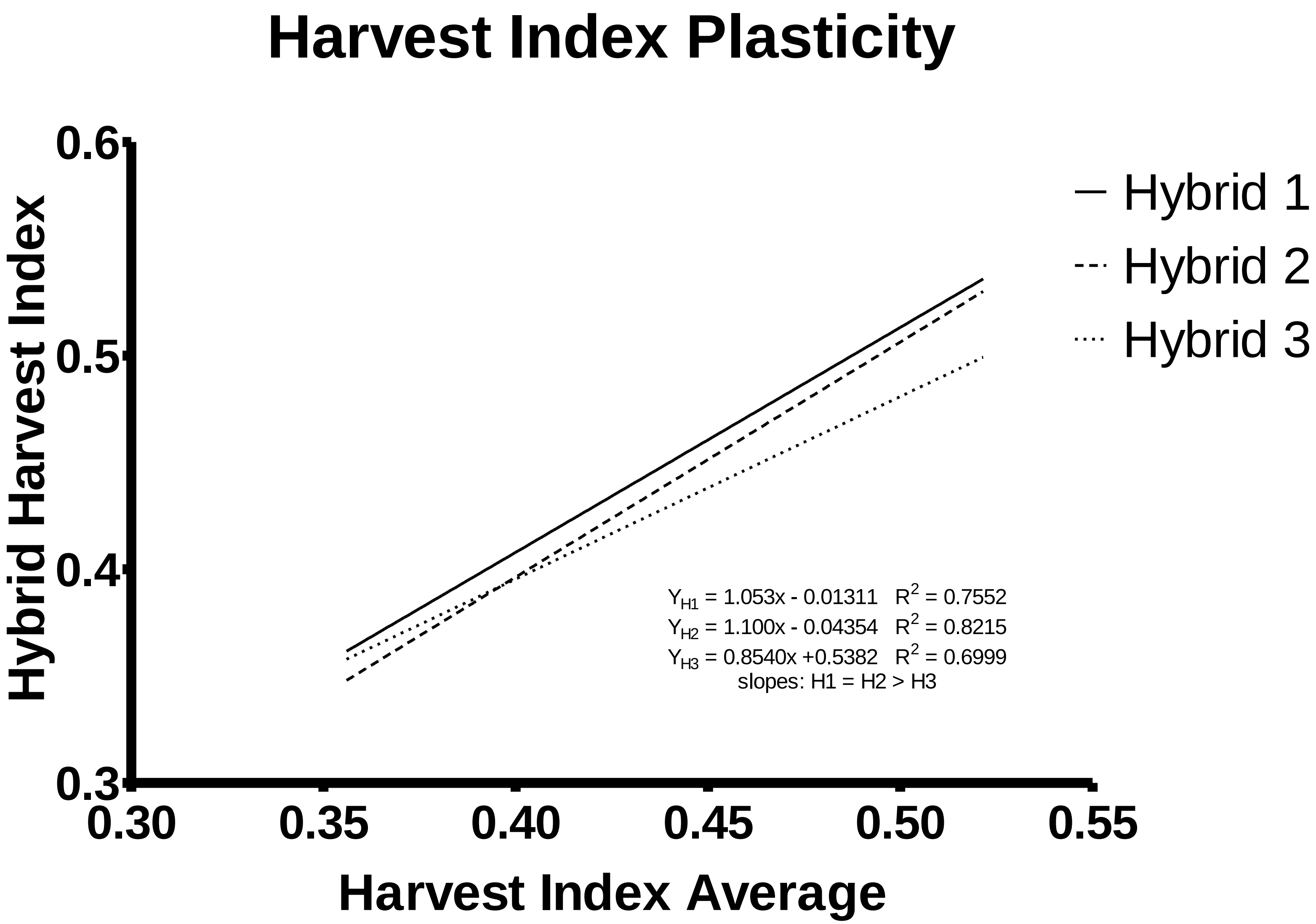
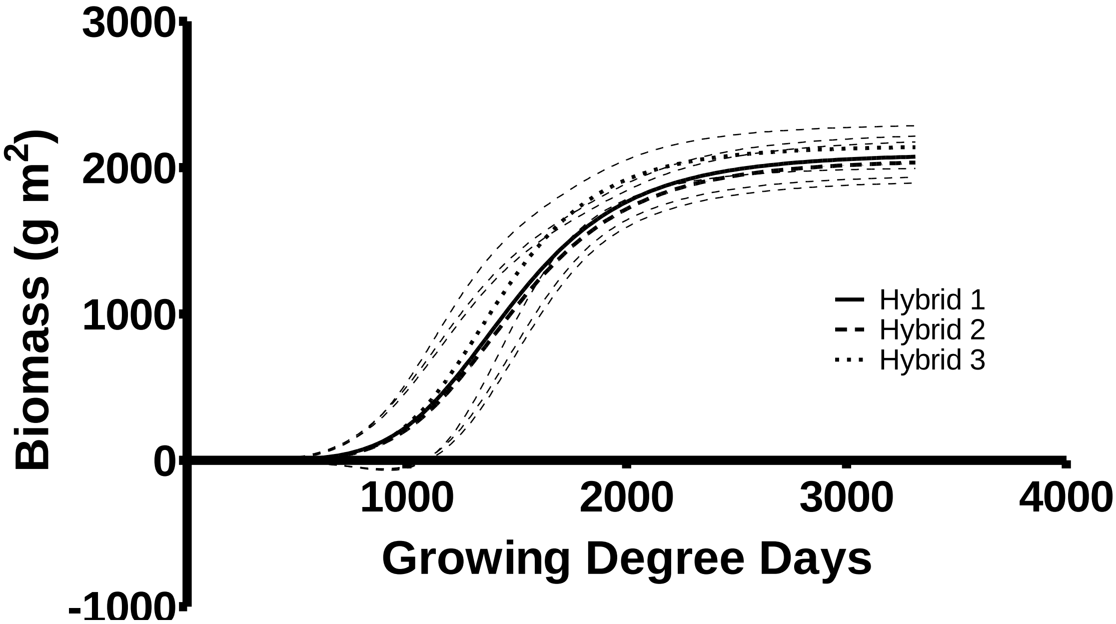
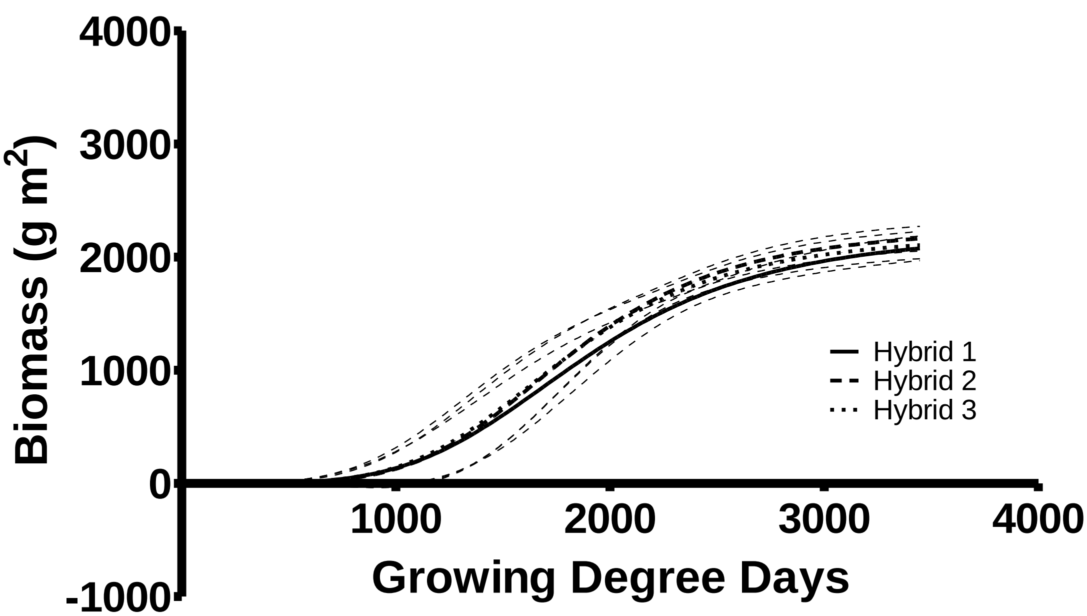


Figure 2.10 Harvest Index Phenotypic Plasticity with the Average Harvest Index of the Three Hybrids on the x-axis and the Individual Hybrid Harvest Index Plotted on the y-axis for all Environments for 2014 and 2015.

Biomass Accumulation for >9.5 Yield Group



Biomass Accumulation for 8.5-9.5 Yield Group



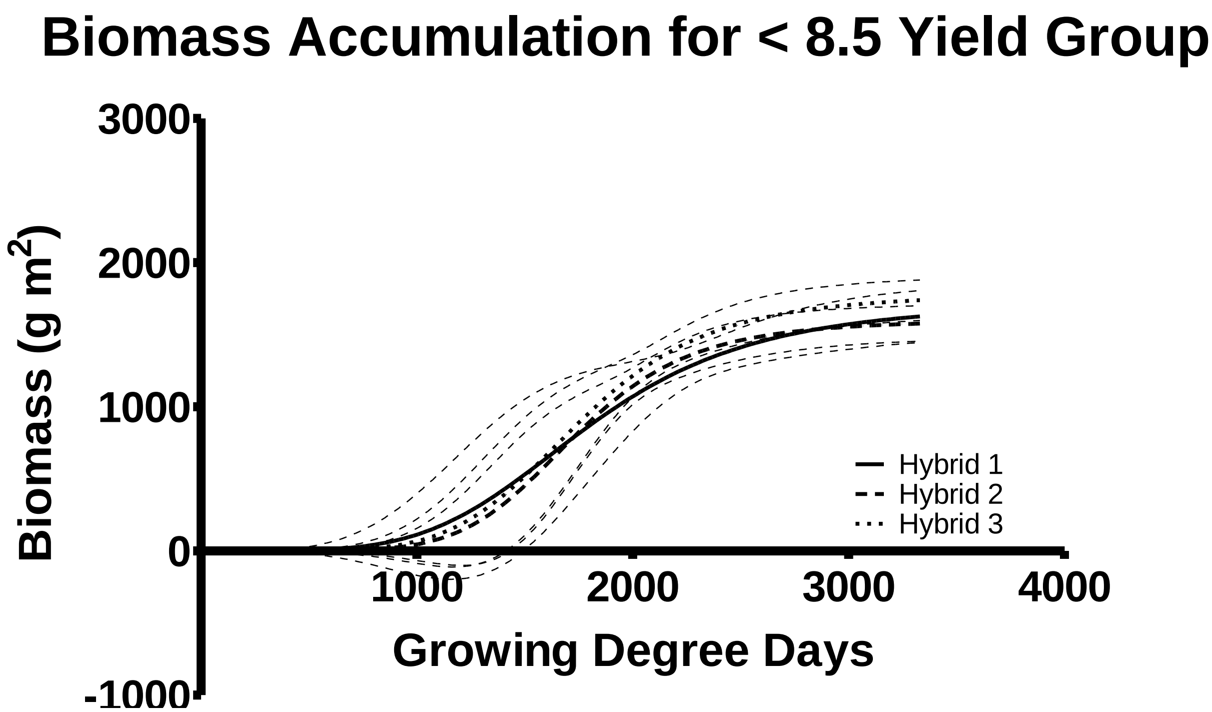


Figure 2.11 Biomass Accumulation throughout the Growing Season for the Different Hybrids in the Environments in each Yield Groupings Plotted with a 95 Percent Confidence Interval.

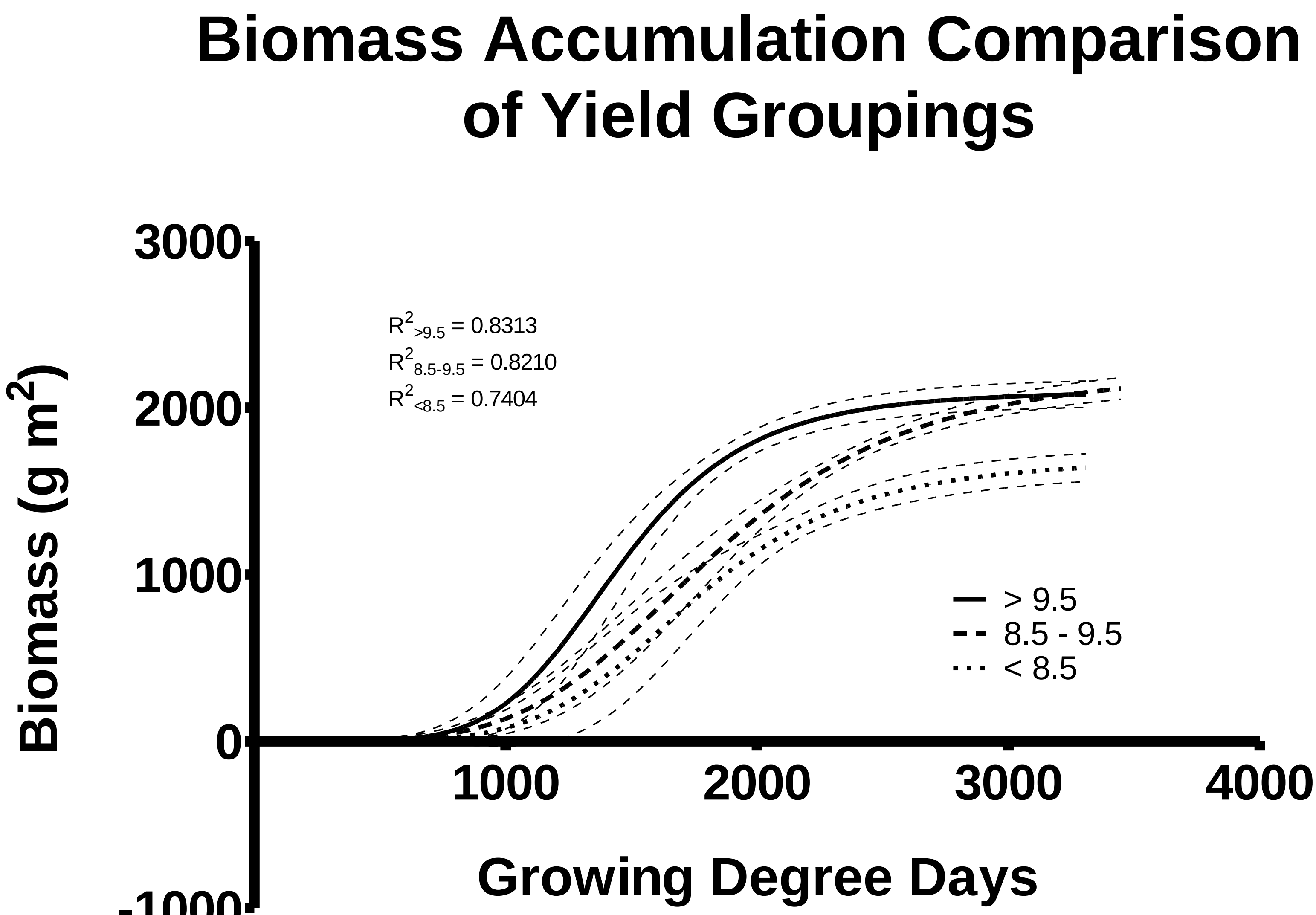


Figure 2.12 Biomass Accumulation Comparison throughout the Growing Season for the different Hybrids Separated by the Yield Groupings Plotted with a 95 Percent Confidence Interval.

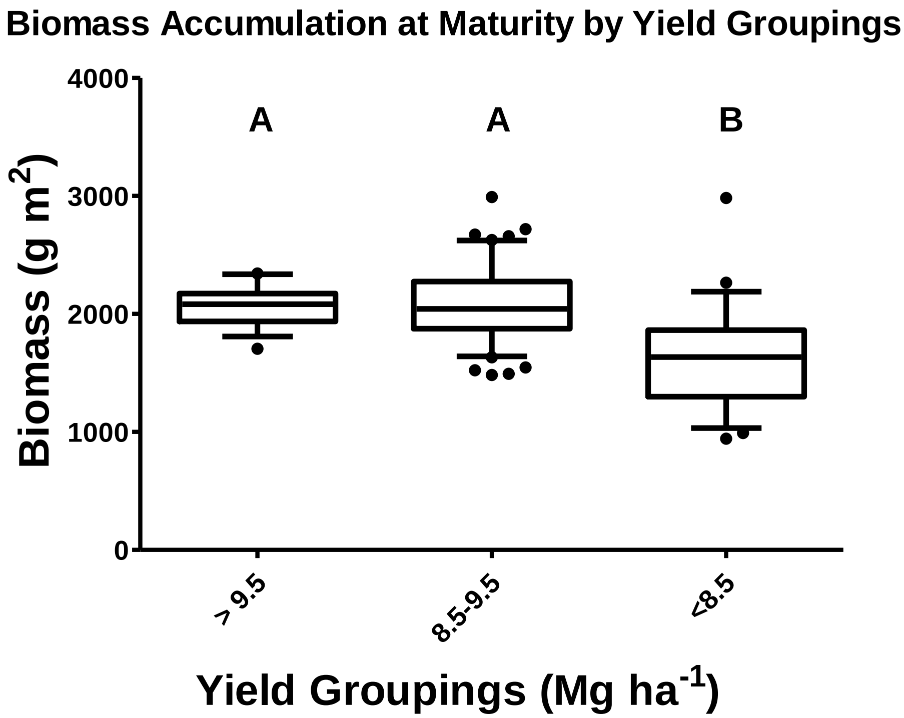


Figure 2.13 Box-plot for the Biomass Accumulation Means at Physiological Maturity for the Different Yield Groupings for all Sites and both Years.

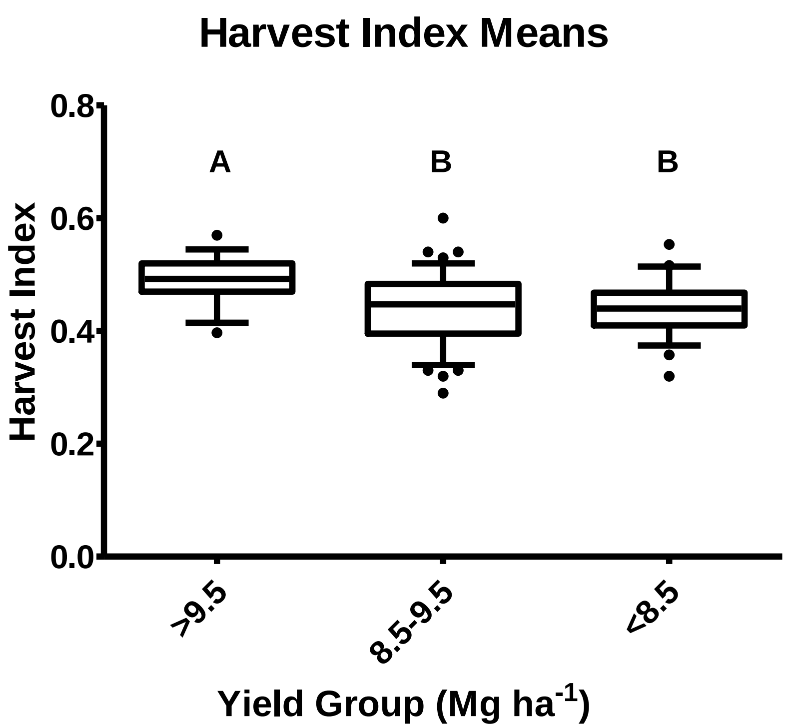


Figure 2.14 Box-plot for Harvest Index Means for the Different Yield Groupings for all Sites and both Years.

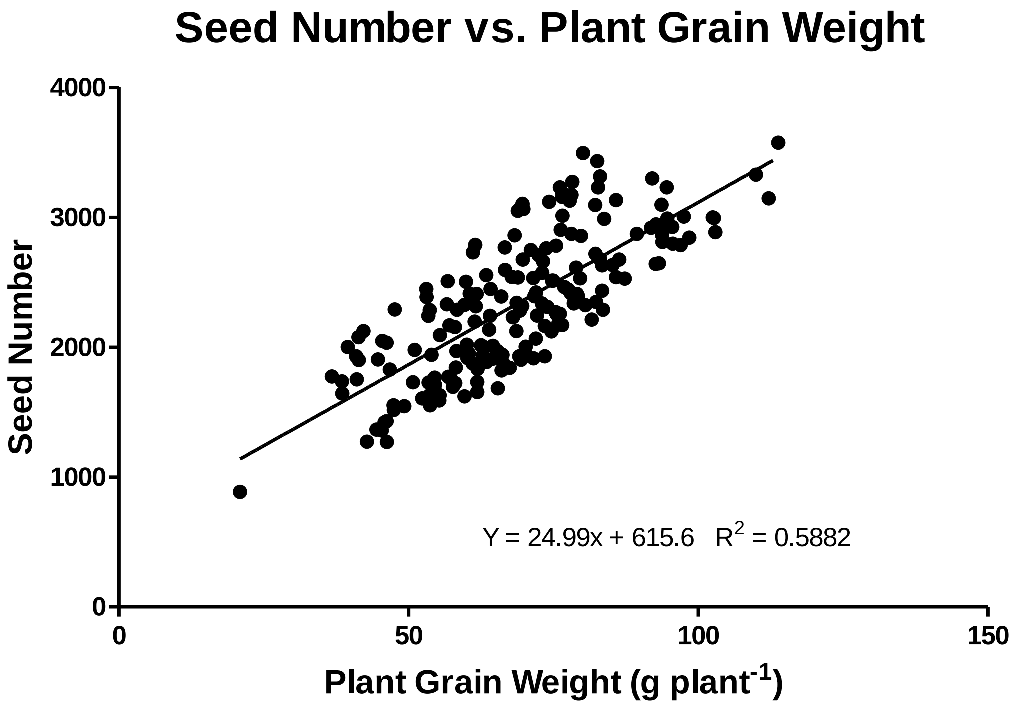


Figure 2.15 Seed Number vs. Individual Plant Grain Weight Regression Line for all Plots in all Environments for 2014 and 2015.

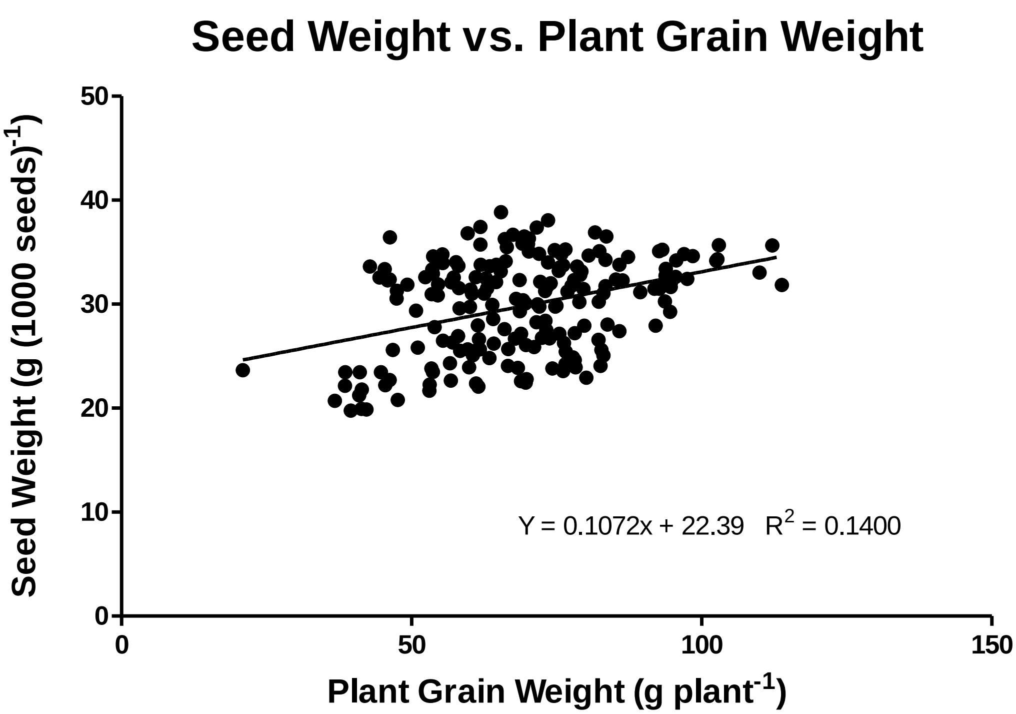


Figure 2.16 Seed Weight vs. Individual Plant Grain Weight Regression Line for all Plots in all Environments for 2014 and 2015.

Table 2.1 Description of Sites used for the 2014 and 2015 Growing Seasons with the Irrigation Regime, Environment Abbreviations, Coordinates, Soil Series, and Average Annual Precipitation.

Year	Site	Irrigation	Environment	Coordinates	Soil series	Average annual precipitation
						mm
2014	Garden City	Dryland	GCD14	37.989320 N, -100.814712W	Ulysses silt loam	491
2014	Hutchinson	Dryland	HTCD14	37.943821 N, -98.110361 W	Nalim loam	795
2014	Hutchinson	33% ET	HTC3314	†	†	†
2014	Hutchinson	66% ET	HTC6614	†	†	†
2014	Hutchinson	Irrigated	HTCIR14	†	†	†
2014	Scandia	Dryland	SCAD14	39.83296 N, -97.8391 W	Crete silt loam	738
2014	Scandia	Irrigated	SCAIR14	†	†	†
2014	Topeka	Dryland	TOPD14	39.07758 N, -95.770367 W	Eudora-Bismarckgrove silt loams	912
2014	Topeka	Irrigated	TOPIR14	†	†	†
2014	Tribune	Dryland	TRID14	38.465219 N, -101.849479 W	Richfield silt loam	460
2015	Garden City	Dryland	GCD15	37.989320 N, -100.814712W	Ulysses silt loam	491
2015	Hutchinson	Dryland	HTCD15	37.943821 N, -98.110361 W	Nalim loam	795
2015	Hutchinson	50% ET	HTC5015	†	†	†
2015	Hutchinson	Irrigated	HTCIR15	†	†	†
2015	Scandia	Dryland	SCAD15	39.83296 N, -97.8391 W	Crete silt loam	738
2015	Scandia	Irrigated	SCAIR15	†	†	†
2015	Topeka	Dryland	TOPD15	39.07758 N, -95.770367 W	Eudora-Bismarckgrove silt loams	912
2015	Topeka	Irrigated	TOPIR15	†	†	†
2015	Tribune	Dryland	TRID15	38.465219 N, -101.849479 W	Richfield silt loam	460

† Values are the same for the entire site, same as the values recorded above

Table 2.2 Field Operations Dates, Yield Goal, Fertilizer Rates, Irrigation Applied, Plot Size, and Number of Replications for Each Environment.

Environment	Planting date	Harvest date	Yield goal	N applied	P applied	K applied	Irrigation	Plot size	Replications
			Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	mm	m x m	
GCD14	6/12/2014	11/17/2014	5.0	56	51	73	0	3.05 X 9.14	4
HTCD14	5/23/2014	11/20/2014	6.3	112	0	0	0	3.05 X 13.72	4
HTC3314	5/22/2014	11/20/2014	7.2	112	0	0	60	3.05 X 13.72	4
HTC6614	5/23/2014	11/20/2014	7.9	157	0	0	130	3.05 X 13.72	4
HTCIR14	5/22/2014	11/24/2014	9.1	225	0	0	199	3.05 X 13.72	4
SCAD14	5/22/2014	11/14/2014	7.9	112	34	0	30	3.05 X 13.72	4
SCAIR14	5/22/2014	11/14/2014	10.1	258	39	0	183	3.05 X 13.72	4
TOPD14	5/21/2014	9/19/2014	8.2	160	58	67	0	3.05 X 9.14	4
TOPIR14	5/21/2014	9/19/2014	10.7	250	58	67	283	3.05 X 9.14	4
TRID14	6/16/2014	11/7/2014	5.0	56	51	73	0	3.05 X 12.19	4
GCD15	6/19/2015	11/4/2015	5.0	90	0	0	0	3.05 X 9.14	4
HTCD15	6/8/2015	10/21/2015	6.3	323	39	0	0	3.05 X 12.19	5
HTC5015	6/8/2015	10/21/2015	7.7	323	39	0	146	3.05 X 12.19	5
HTCIR15	6/8/2015	10/21/2015	9.1	323	39	0	292	3.05 X 12.19	5
SCAD15	5/19/2015	11/24/2015	7.9	112	0	0	0	3.05 X 13.72	5
SCAIR15	5/19/2015	11/24/2015	10.1	258	45	45	159	3.05 X 13.72	5
TOPD15	5/19/2015	9/30/2015	8.2	112	0	0	0	3.05 X 9.14	4
TOPIR15	5/19/2015	9/30/2015	10.7	225	45	11	95	3.05 X 9.14	4
TRID15	6/2/2015	10/17/2015	5.0	80	44	0	0	3.05 X 12.19	4

Table 2.3 Target and Observed Plant Densities with Statistical Significant Differences between the Hybrid Means for the 2014 Growing Season.

Environment	Hybrid	Target plant density	Observed plant density		p-value
		1000 Plants ha^{-1}	1000 Plants ha^{-1}		
GCD14	h2	99	-		
GCD14	h3	99	-		
GCD14	h4	99	-		-
HTC3314	h1	148	141		
HTC3314	h2	148	144		
HTC3314	h3	148	139		0.555
HTC6614	h1	185	162		
HTC6614	h2	185	150		
HTC6614	h3	185	131		0.221
HTCD14	h1	111	113	A	
HTCD14	h2	111	118	A	
HTCD14	h3	111	105	B	0.010
HTCIR14	h1	222	184		
HTCIR14	h2	222	183		
HTCIR14	h3	222	178		0.308
SCAD14	h1	124	124		
SCAD14	h2	124	131		
SCAD14	h3	124	136		0.502
SCAIR14	h1	222	202	B	
SCAIR14	h2	222	242	A	
SCAIR14	h3	222	227	A	0.014
TOPD14	h1	148	140		
TOPD14	h2	148	147		
TOPD14	h3	148	146		0.142
TOPIR14	h1	222	210		
TOPIR14	h2	222	211		
TOPIR14	h3	222	214		0.138
TRID14	h2	99	-		
TRID14	h3	99	-		
TRID14	h4	99	-		-

Values with different letters are significantly different (p-value < 0.05)

Table 2.4 Target and Observed Plant Densities with Statistical Significant Differences between the Hybrid Means for the 2015 Growing Season.

Environment	Hybrid	Target plant density	Observed plant density		p-value
		1000 Plants ha^{-1}	1000 Plants ha^{-1}		
GCD15	h2	99	-		
GCD15	h3	99	-		
GCD15	h4	99	-		
HTC5015	h1	167	166		
HTC5015	h2	167	170		
HTC5015	h3	167	169		0.716
HTCD15	h1	111	109	B	
HTCD15	h2	111	121	A	
HTCD15	h3	111	119	A	0.010
HTCIR15	h1	222	213		
HTCIR15	h2	222	219		
HTCIR15	h3	222	217		0.569
SCAD15	h1	124	99	B	
SCAD15	h2	124	106	B	
SCAD15	h3	124	128	A	0.001
SCAIR15	h1	222	198		
SCAIR15	h2	222	199		
SCAIR15	h3	222	218		0.081
TOPD15	h1	148	120		
TOPD15	h2	148	115		
TOPD15	h3	148	128		0.361
TOPIR15	h1	222	181		
TOPIR15	h2	222	177		
TOPIR15	h3	222	194		0.096
TRID15	h2	99	-		
TRID15	h3	99	-		
TRID15	h4	99	-		

Values with different letters are significantly different (p-value < 0.05)

Table 2.5 Irrigation Dates and Their Respective Amounts Applied at Each Environment for 2014 and 2015.

Environment	Dates applied	Respective irrigation amounts (mm)	Total irrigation (mm)
HTC3314	28-May, 25-Jul, 31-Jul, 13-Aug, 17-Aug, 20-Aug, 24-Aug, 30-Aug	6.1, 9.4, 7.6, 6.1, 7.6, 7.6, 7.6, 7.6	60
HTC6614	28-May, 25-Jul, 31-Jul, 13-Aug, 17-Aug, 20-Aug, 24-Aug, 30-Aug	13.2, 20.6, 16.5, 13.2, 16.5, 16.5, 16.5, 16.5	130
HTCIR14	28-May, 25-Jul, 31-Jul, 13-Aug, 17-Aug, 20-Aug, 24-Aug, 30-Aug	20.3, 31.8, 25.4, 20.3, 25.4, 25.4, 25.4, 25.4	199
SCAD14 †	11-Jul	30.5	30
SCAIR14	11-Jul, 17-Jul, 25-Jul, 31-Jul, 8-Aug, 28-Aug	30.5, 30.5, 30.5, 30.5, 30.5, 30.5	183
TOPIR14	1-Jul, 3-Jul, 7-Jul, 10-Jul, 15-Jul ,21-Jul, 28-Jul, 1-Aug, 6-Aug, 12-Aug, 17-Aug, 22-Aug, 27-Aug	24.2, 23.8, 24.0, 20.7, 22.3, 23.5, 23.5, 22.9, 16.9, 22.9, 17.7, 18.1, 22.9	283
HTC5015	1-Jul, 5-Jul, 14-Jul, 18-Jul, 24-Jul, 29-Jul, 13-Aug, 15-Aug	19.1, 19.1, 19.1, 19.1, 19.1, 19.1, 15.9, 15.9	146
HTCIR15	1-Jul, 5-Jul, 14-Jul, 18-Jul, 24-Jul, 29-Jul, 13-Aug, 15-Aug	38.1, 38.1, 38.1, 38.1, 38.1, 38.1, 31.8, 31.8	292
SCAIR15	6-Jul, 16-Jul, 22-Jul, 19-Aug, 11-Sep	31.8, 31.8, 31.8, 31.8, 31.8	159
TOPIR15	1-Jul, 27-Jul, 3-Aug, 14-Aug, 25-Aug	22.1, 18.3, 18.3, 18.3, 18.3	95

† Malfunction in irrigation system made application of water when none should have been applied

Table 2.6 Means for Yield, Biomass, Harvest Index, Seed Weight, and Seed Number with Statistical Differences for the 2014 Growing Season.

Environment	Hybrid	Yield		Biomass		Harvest index	Seed weight		Seed number	
		Mg ha^{-1}		g m^{-2}			grams (1000 seeds)$^{-1}$		seeds panicle^{-1}	
GCD14	h2	3.55		-		-	-		-	
GCD14	h3	4.17		-		-	-		-	
GCD14	h4	3.16		-		-	-		-	
HTC3314	h1	8.08		1846		0.44	26.5		2908	
HTC3314	h2	8.02		1835		0.44	26.7		2660	
HTC3314	h3	8.18		1934		0.43	26.0		2624	
HTC6614	h1	8.74	B	1969		0.45	23.8	B	2296	
HTC6614	h2	9.54	A	2378		0.40	22.2	B	2414	
HTC6614	h3	9.17	AB	2224		0.42	26.2	A	2033	
HTCD14 †	h1	2.78	C	709	C	0.39	21.4		2125	
HTCD14 †	h2	4.07	B	1015	B	0.40	20.9		2132	
HTCD14 †	h3	5.52	A	1349	A	0.41	23.8		2095	
HTCIR14 ¶	h1	7.66		1767		0.44	25.9		2756	
HTCIR14 ¶	h2	6.73		1487		0.46	28.0		2779	
HTCIR14 ¶	h3	7.50		1825		0.44	28.1		2657	
SCAD14 ‡	h1	8.78	B	2339		0.38	24.2		2990	
SCAD14 ‡	h2	9.42	A	2574		0.37	24.0		2965	
SCAD14 ‡	h3	8.72	B	2539		0.35	24.9		2394	
SCAIR14	h1	8.81		2458		0.36	23.5		2869	
SCAIR14	h2	8.65		2493		0.35	24.5		2781	
SCAIR14	h3	8.81		2439		0.36	25.2		2859	
TOPD14	h1	9.47		1868		0.51	31.7		2503	
TOPD14	h2	9.02		1685		0.54	35.0		2480	
TOPD14	h3	8.96		1728		0.52	32.1		2468	
TOPIR14	h1	11.23	A	2100		0.54	32.1		2820	A
TOPIR14	h2	10.45	AB	2047		0.51	34.3		2036	B
TOPIR14	h3	10.24	B	2037		0.51	35.1		2063	B
TRID14	h2	6.10		-		-	-		-	
TRID14	h3	6.53		-		-	-		-	
TRID14	h4	7.05		-		-	-		-	

Values with different letters are significantly different (p-value < 0.05)
† Significant lodging affecting hybrids differently
¶ Lodging affecting all hybrids equally and a consequential reduction in yields
‡ Malfunction in the irrigation system made application on July 11

Table 2.7 Means for Yield, Biomass, Harvest Index, Seed Weight, and Seed Number with Statistical Differences for the 2015 Growing Season.

Environment	Hybrid	Yield	Biomass	Harvest index		Seed weight		Seed number	
		Mg ha^{-1}	g m^{-2}			grams (1000 seeds)$^{-1}$		seeds panicle^{-1}	
GCD15 †	h2	10.82	-	-		-		-	
GCD15	h3	9.98	-	-		-		-	
GCD15	h4	9.19	-	-		-		-	
HTC5015 ¶	h1	8.84	1806	0.46		32.8		1912	
HTC5015 ¶	h2	8.87	1934	0.46		32.8		1906	
HTC5015 ¶	h3	8.66	1818	0.45		32.6		1623	
HTCD15	h1	7.90	1566	0.51	A	35.8		2028	
HTCD15	h2	7.83	1609	0.48	AB	34.8		2002	
HTCD15	h3	8.08	1826	0.44	B	35.7		1934	
HTCIR15	h1	9.21	2054	0.45	A	32.9	AB	1706	
HTCIR15	h2	9.57	2146	0.44	A	33.7	A	1615	
HTCIR15	h3	8.94	2150	0.41	B	31.6	B	1605	
SCAD15	h1	9.18	1857	0.49	A	31.5		2858	
SCAD15	h2	8.86	1908	0.46	B	33.4		3001	
SCAD15	h3	8.87	1884	0.47	B	33.9		2450	
SCAIR15	h1	8.99	1869	0.48		33.2		2758	
SCAIR15	h2	9.46	2021	0.47		34.6		2390	
SCAIR15	h3	8.51	1847	0.46		34.8		2269	
TOPD15 ‡	h1	10.34	2066	0.50	A	30.5		2443	B
TOPD15 ‡	h2	10.60	2033	0.52	A	32.5		2838	A
TOPD15 ‡	h3	9.85	2138	0.46	B	31.2		2166	B
TOPIR15 ‡	h1	9.88	2008	0.49	A	30.5		2158	
TOPIR15 ‡	h2	9.84	2090	0.47	A	32.0		1867	
TOPIR15 ‡	h3	8.74	2067	0.42	B	31.1		1618	
TRID15	h2	7.77	-	-		-		-	
TRID15	h3	8.40	-	-		-		-	
TRID15	h4	8.43	-	-		-		-	

Values with different letters are significantly different (p-value < 0.05)
† Two plots removed from data due to lodging
¶ Four plots removed from data due to late planting and resulting lower yields
‡ Bird Damage affecting all hybrids equally

Table 2.8 SPAD, Canopy Temperature, and Days to Flowering Measurements Recorded for the 2014 Growing Season.

Environment	Hybrid	SPAD MV		SPAD FL		SPAD MR		Canopy temp MV	Canopy temp FL		Canopy temp MR	Days to flowering	
								°C	°C		°C	days	
GCD14	h2	-		-		-		-	-		-	-	
GCD14	h3	-		-		-		-	-		-	-	
GCD14	h4	-		-		-		-	-		-	-	
HTC3314	h1	53.15		53.15		55.00		38.75	28.68		34.45	77.00	
HTC3314	h2	51.93		53.40		50.83		38.53	29.03		34.70	76.75	
HTC3314	h3	50.33		50.85		51.73		39.43	28.78		34.38	80.75	
HTC6614	h1	48.65		52.58		63.50	A	39.18	27.15		31.95	74.50	C
HTC6614	h2	54.60		52.35		61.80	AB	38.70	26.53		32.20	76.50	B
HTC6614	h3	50.93		51.53		56.95	B	39.15	26.28		32.05	80.50	A
HTCD14	h1	54.83	A	54.43	A	25.95		39.20	30.33		35.23	65.00	C
HTCD14	h2	53.75	AB	50.45	B	25.98		39.55	31.10		34.60	66.25	B
HTCD14	h3	50.53	B	47.18	C	37.08		39.50	30.35		34.93	69.50	A
HTCIR14	h1	54.03	A	53.03		56.63		38.75	28.70		32.10	72.50	C
HTCIR14	h2	54.83	A	55.00		62.50		38.20	28.53		32.50	75.25	B
HTCIR14	h3	50.88	B	53.15		58.60		38.50	28.60		32.30	78.50	A
SCAD14	h1	54.38		54.13		54.10		22.43	36.20		27.45	72.50	
SCAD14	h2	55.05		53.58		57.45		22.58	35.70		27.65	71.75	
SCAD14	h3	51.33		50.65		53.13		22.65	35.58		27.38	71.50	
SCAIR14	h1	54.35	A	58.40		58.45	A	22.35	33.10	B	27.35	71.25	
SCAIR14	h2	53.05	AB	56.90		56.95	A	21.85	33.98	A	27.00	72.50	
SCAIR14	h3	51.15	B	54.78		53.23	B	22.20	33.70	A	27.03	72.00	
TOPD14	h1	53.23		54.25	A	50.18		31.35	30.20		33.33	64.50	B
TOPD14	h2	54.30		55.03	A	51.23		31.03	29.78		33.85	66.00	A
TOPD14	h3	50.85		47.50	B	47.00		31.33	30.23		33.63	66.00	A
TOPIR14	h1	52.28		57.63		58.35		29.10	29.48		30.45	63.50	B
TOPIR14	h2	53.88		53.73		56.40		29.10	29.50		30.35	65.75	A
TOPIR14	h3	50.70		53.05		56.58		29.50	28.88		30.43	66.25	A
TRID14	h2	-		-		-		-	-		-	-	
TRID14	h3	-		-		-		-	-		-	-	
TRID14	h4	-		-		-		-	-		-	-	

Values with different letters are significantly different (p-value < 0.05)
MV, FL, and MR are abbreviations for panicle initiation, flowering, and hard dough stages respectively

Table 2.9 SPAD, Canopy Temperature, and Days to Flowering Measurements Recorded for the 2015 Growing Season.

Environment	Hybrid	SPAD FL		SPAD MR		Canopy temp FL		Canopy temp MR	Days to flowering	
						°C		°C	days	
GCD15	h2	-		-		-		-	-	
GCD15	h3	-		-		-		-	-	
GCD15	h4	-		-		-		-	-	
HTC5015	h1	55.27		52.87		31.99		26.47	58.98	
HTC5015	h2	56.52		58.80		32.36		25.96	59.40	
HTC5015	h3	56.23		55.73		31.89		26.77	58.65	
HTCD15	h1	59.04	A	60.56	A	31.90	B	26.88	56.20	
HTCD15	h2	60.04	A	61.12	A	32.66	A	27.00	58.40	
HTCD15	h3	57.22	B	55.44	B	32.14	B	26.36	58.20	
HTCIR15	h1	56.66	A	57.30		32.20		25.90	58.60	B
HTCIR15	h2	57.40	A	58.54		32.16		25.88	60.00	A
HTCIR15	h3	53.24	B	54.44		32.62		25.98	60.40	A
SCAD15	h1	57.18	A	54.10		-		26.68	75.60	B
SCAD15	h2	56.82	A	54.08		-		26.64	78.20	A
SCAD15	h3	52.68	B	50.44		-		26.68	77.60	A
SCAIR15	h1	59.10	A	58.26		-		25.32	73.20	B
SCAIR15	h2	55.34	B	57.70		-		25.36	75.60	A
SCAIR15	h3	51.92	C	55.52		-		25.38	76.20	A
TOPD15	h1	58.70	A	57.28		27.95		27.25	66.75	C
TOPD15	h2	59.95	A	57.60		28.35		26.88	69.75	B
TOPD15	h3	55.45	B	58.20		29.10		26.98	71.50	A
TOPIR15	h1	58.00	A	57.68		26.70		28.38	67.50	B
TOPIR15	h2	57.45	A	58.45		26.38		28.25	70.25	A
TOPIR15	h3	54.28	B	57.13		27.45		27.08	70.50	A
TRID15	h2	-		-		-		-	-	
TRID15	h3	-		-		-		-	-	
TRID15	h4	-		-		-		-	-	

Values with different letters are significantly different (p-value < 0.05)
MV, FL, and MR are abbreviations for panicle initiation, flowering, and hard dough stages respectively

Table 2.10 ANOVA Tables for Yields, Harvest Index, Biomass, Seed Number, Seed Weight, and SPAD Measurements with Hybrid, Environment, and the Interaction as Fixed Effects for all Environments in the 2014 and 2015 Growing Season.

Measurements	Effect	Num DF	Den DF	F Value	Pr > F
Yield	HYB	2	154.8	0.52	0.5984
	ENV	14	155	41.09	<.0001
	ENV*HYB	28	154.8	1.62	0.0354
Yield (Garden City and Tribune)	HYB	2	36	0.99	0.38
	ENV	3	36	34.43	<.0001
	ENV*HYB	6	36	0.3	0.9341
HI	HYB	2	144	10.12	<.0001
	ENV	14	144	41.7	<.0001
	ENV*HYB	28	144	1.58	0.0448
Biomass Harvest	HYB	2	140.5	2.32	0.1024
	ENV	14	140.6	30.29	<.0001
	ENV*HYB	28	140.5	1.26	0.1913
Seed Number	HYB	2	140.9	9.51	0.0001
	ENV	14	140.9	16.11	<.0001
	ENV*HYB	28	140.9	0.95	0.5378
Seed Weight	HYB	2	140.9	5.11	0.0072
	ENV	14	141	67.89	<.0001
	ENV*HYB	28	140.8	1.27	0.1828
Biomass MV	HYB	2	102.8	2.89	0.0603
	ENV	11	103.8	45.4	<.0001
	ENV*HYB	22	102.7	1.64	0.052
Biomass FL	HYB	2	115.8	6.12	0.003
	ENV	14	115.5	25.6	<.0001
	ENV*HYB	28	115.7	1.18	0.2691
Biomass MR	HYB	2	110	0.78	0.4613
	ENV	12	110	8.2	<.0001
	ENV*HYB	24	110	0.97	0.5126
SPAD MV	HYB	2	72	19.75	<.0001
	ENV	7	72	1.6	0.1506
	ENV*HYB	14	72	1.66	0.0836
SPAD FL	HYB	2	146	45.52	<.0001
	ENV	14	146	14.7	<.0001
	ENV*HYB	28	146	1.84	0.0109
SPAD MR	HYB	2	142.9	3.89	0.0227
	ENV	14	142.9	45.22	<.0001
	ENV*HYB	28	142.9	1.96	0.0056

MV, FL, and MR are abbreviations for panicle initiation, flowering, and hard dough stages respectively
Garden City and Tribune Sites are excluded due to differing hybrids

Table 2.11 ANOVA Tables for Canopy Temperature Measurements with Hybrid, Environment, and the Interaction as Fixed Effects for all Environments in the 2014 and 2015 Growing Season.

Measurement	Effect	Num DF	Den DF	F Value	Pr > F
Canopy Temp MV	HYB	2	69	1.93	0.1528
	ENV	7	69	1363.87	<.0001
	ENV*HYB	14	69	0.39	0.9725
Canopy Temp FL	HYB	2	118.2	0.38	0.6858
	ENV	12	118.5	140.6	<.0001
	ENV*HYB	24	118.2	1.04	0.4242
Canopy Temp MR	HYB	2	142.8	0.68	0.509
	ENV	14	142.8	358.64	<.0001
	ENV*HYB	28	142.8	0.79	0.7619

MV, FL, and MR are abbreviations for panicle initiation, flowering, and hard dough stages respectively

Garden City and Tribune Sites are excluded due to differing hybrids

Table 2.12 Environment Means for Yield, Harvest Index, Biomass, Seed Number, and Seed Weight with Statistical Differences for all Environments in 2014 and 2015.

Environment	Yield		HI		Biomass †		Seed number		Seed weight	
	Mg ha^{-1}				g m^{2}		Seeds panicle^{-1}		g (1000 seeds)$^{-1}$	
HTC3314	8.13	D	0.44	FG	1867	E	2730	AB	26.4	F
HTC5015	8.79	C	0.45	DEF	1874	DE	1871	FG	32.7	CDE
HTC6614	9.18	BC	0.42	GH	2186	B	2248	CDE	24.0	G
HTCD14	4.16	F	0.40	H	1020	G	2117	DEF	22.2	H
HTCD15	7.93	DE	0.48	BC	1667	EF	1988	EF	35.4	A
HTCIR14	7.33	E	0.45	EF	1639	F	2726	AB	27.3	F
HTCIR15	9.24	BC	0.43	FG	2117	B	1642	G	32.7	CD
SCAD14	9.01	BC	0.37	I	2428	A	2854	A	24.5	G
SCAD15	8.99	BC	0.48	BC	1883	DE	2770	A	32.9	BC
SCAIR14	8.79	C	0.36	I	2459	A	2836	A	24.4	G
SCAIR15	9.01	BC	0.47	CD	1912	CDE	2472	BC	34.2	AB
TOPD14	9.18	BC	0.52	A	1756	EF	2483	BC	32.9	BCD
TOPD15	10.30	A	0.49	B	2075	BC	2482	BC	31.4	DE
TOPIR14	10.67	A	0.52	A	2057	BCD	2306	CD	33.8	BC
TOPIR15	9.52	B	0.46	CD	2051	BCD	1881	F	31.2	E

Values with different letters are significantly different (p-value < 0.05)

† The following additional pairs are significantly different: (TOPIr14,SCAD15).

Garden City and Tribune Sites are excluded due to differing hybrids

Table 2.13 Hybrid Means for Yield, Harvest Index, Biomass, Seed Number, and Seed Weight with Statistical Differences across all Environments in 2014 and 2015.

	Yield	HI		Biomass	Seed number		Seed weight		Biomass MV	Biomass FL		Biomass MR
	Mg ha^{-1}			g m^2	Seeds panicle^{-1}		g (1000 seeds)$^{-1}$		g m^2	g m^2		
Hybrid 1	8.69	0.46	A	1885	2481	A	29.1	B	305	1027	B	1805
Hybrid 2	8.75	0.45	A	1947	2391	A	29.9	A	287	1117	AB	1862
Hybrid 3	8.61	0.44	B	1966	2209	B	30.2	A	326	1205	A	1914

Values with different letters are significantly different (p-value < 0.05)
MV, FL, and MR are abbreviations for panicle initiation, flowering, and hard dough stages respectively
Garden City and Tribune Sites are excluded due to differing hybrids

Table 2.14 Hybrid Means for SPAD with Statistical Differences across all Environments in 2014 and 2015.

	SPAD MV		SPAD FL		SPAD MR	
Hybrid 1	53.1	A	53.1	A	54.7	AB
Hybrid 2	53.9	A	53.9	A	55.3	A
Hybrid 3	50.8	B	50.8	B	53.4	B

Values with different letters are significantly different (p-value < 0.05)

Appendix A - Soil Volumetric Water Content Data

Table on Changes in Soil Profile Volumetric Water Content

As discussed in Materials and Methods, the factory calibration equation was used for volumetric water content calculations. For exact values of volumetric water content, a neutron probe calibration would be needed at each site. Thus, valid comparisons cannot be made across environments; but within each environment, the change in volumetric water content ($\Delta\theta$) between the treatments of hybrid can be compared against each other without changing the statistical differences if the calibration equation is changed. Values for hybrids in this section are not meant to be absolute, but rather relative to each other. Each change in volumetric water content calculation at each depth in a tube were multiplied by the depth of the soil for which the calculation was measured and summed to get the total change in depth of water for the soil profile (ΔW) between different physiological growth stages. Table 2.15 shows the changes in water content (ΔW) between different physiological growth stages and the statistical differences between hybrids.

Table 2.15 Hybrid Means of the Total Change in Soil Profile Volumetric Water Contents throughout the Growing Season for all Environments in 2014 and 2015.

Environment	Hybrid	ΔW_{EM-MT}	ΔW_{EM-FL}	ΔW_{FL-MT}	ΔW_{EM-MV}	ΔW_{MV-FL}	ΔW_{FL-MR}	ΔW_{MR-MT}
		mm	mm	mm	mm	mm	mm	mm
GCD14	h2	77.6	74.1	3.5	-	-	-	-
GCD14	h3	105.1	84.0	21.1	-	-	-	-
GCD14	h4	116.5	74.8	41.8	-	-	-	-
GCD15	h2	162.2	144.0	18.2	-	-	-	-
GCD15	h3	168.1	125.4	42.7	-	-	-	-
GCD15	h4	172.5	128.9	43.6	-	-	-	-
HTC3314	h1	108.1	54.5	53.7	24.57	29.88	52.05	1.60
HTC3314	h2	110.3	53.6	56.6	26.26	27.35	45.83	10.82

HTC3314	h3	104.4		48.2		56.2		23.51		24.70	46.85		9.36	
HTC5015	h1	68.8	B	27.6	B	41.9		4.21		19.06	-12.66		55.39	
HTC5015	h2	77.0	A	36.1	A	40.9		8.90		27.22	-10.68		51.55	
HTC5015	h3	80.1	A	37.4	A	43.4		7.69		25.38	-6.02		51.07	
HTC6614	h1	91.2		23.5		67.7		11.47		12.00	37.90		29.84	
HTC6614	h2	93.4		28.2		65.2		17.61		10.64	37.77		27.38	
HTC6614	h3	91.3		23.5		67.8		17.26		6.21	35.95		31.88	
HTCD14	h1	101.0		83.6		17.5	B	16.27		67.30	14.07	B	3.40	
HTCD14	h2	101.9		75.4		26.5	B	15.67		59.78	23.29	B	3.20	
HTCD14	h3	117.9		76.2		41.7	A	15.88		60.30	36.24	A	5.43	
HTCD15	h1	146.3		93.9		52.4	A	15.38		78.56	15.00		37.36	
HTCD15	h2	128.3		93.0		35.4	B	13.73		79.23	1.13		34.25	
HTCD15	h3	138.6		87.9		50.8	A	21.16		66.69	-1.19		51.96	
HTCIr14	h1	95.1		19.9		75.2		20.00		-0.12	29.61		45.62	
HTCIr14	h2	75.6		22.8		52.8		19.13		3.65	25.20		27.61	
HTCIr14	h3	83.8		20.7		63.1		26.28		-5.62	30.38		32.76	
HTCIr15	h1	56.0		4.2		51.7		-0.17		4.37	-2.87		54.61	
HTCIr15	h2	44.9		7.0		37.9		-2.15		9.15	-12.13		50.08	
HTCIr15	h3	56.9		3.0		53.9		0.56		2.42	-3.72		57.61	
SCAD14	h1	50.5		64.5	B	-14.1		3.98	B	60.58	-19.55		5.49	
SCAD14	h2	65.0		74.9	AB	-10.0		12.53	AB	62.41	-17.25		7.28	
SCAD14	h3	57.4		77.9	A	-20.5		16.37	A	61.51	-28.08		7.61	
SCAD15	h1	123.3	B	42.1		81.2	AB	38.75		3.34	86.91		-5.72	
SCAD15	h2	134.9	A	42.6		92.3	A	41.12		1.53	94.91		-2.65	
SCAD15	h3	130.4	AB	53.8		76.6	B	44.67		9.11	80.08		-3.47	
SCAIr14	h1	27.0		27.7		-0.7		6.57		21.17	-13.24		12.53	A
SCAIr14	h2	33.2		39.1		-5.9		14.57		24.52	-15.66		9.80	AB
SCAIr14	h3	23.9		32.4		-8.5		11.50		20.90	-15.03		6.58	B
SCAIr15	h1	113.8		21.1		92.7		27.07		-5.92	73.69		19.00	
SCAIr15	h2	111.3		23.6		87.7		31.85		-8.22	69.77		17.95	

SCAIr15	h3	112.6		24.2	88.4	31.99	-7.82		74.76	13.69
TOPD14	h1	149.3		119.1	30.3	26.53	92.54		68.04	-37.77
TOPD14	h2	129.7		115.2	14.4	28.53	86.71		62.04	-47.61
TOPD14	h3	122.0		113.1	9.0	29.12	83.97		59.78	-50.82
TOPD15	h1	98.5		45.1	53.5	45.17	-0.08		55.40	-1.94
TOPD15	h2	97.9		46.9	51.0	40.53	6.37		52.55	-1.58
TOPD15	h3	94.1		44.0	50.1	40.33	3.63		52.63	-2.51
TOPIr14	h1	49.8		63.8	-14.0	26.42	37.38		3.77	-17.77
TOPIr14	h2	50.8		67.9	-17.1	22.22	45.69		2.55	-19.66
TOPIr14	h3	42.4		56.2	-13.8	27.89	28.33		-6.77	-7.05
TOPIr15	h1	60.1		23.0	37.1	27.65	-4.68	AB	29.89	7.22
TOPIr15	h2	64.3		27.8	36.5	28.14	-0.37	A	29.21	7.32
TOPIr15	h3	63.2		23.8	39.4	35.49	-11.64	B	35.02	4.34
TRID14	h2	129.1	A	76.1	53.0	-	-		-	-
TRID14	h3	125.9	A	74.9	51.0	-	-		-	-
TRID14	h4	112.0	B	67.8	44.2	-	-		-	-
TRID15	h2	79.0		45.2	33.7	-	-		-	-
TRID15	h3	81.5		47.1	34.4	-	-		-	-
TRID15	h4	74.6		40.2	34.4	-	-		-	-

Values with different letters are significantly different (p-value < 0.05)

EM, MV, FL, MR, and MT are abbreviations for Emergence, Mid-Vegetative (panicle initiation), Flowering, Mid-Reproductive (hard dough), and Maturity stages respectively

$\Delta\theta$ stands for the change in volumetric water content for the entire soil profile between the two physiological stages noted

Soil Neutron Probe was not calibrated so values are not absolute, but values will remain in their respective order with the same statistical significance as changing the equation from calibration does not change the ratio between plots within an environment. Can only be compared within an environment, no valid comparison between different environments.

Statistical Differences in Changes in Soil Volumetric Water Contents at Depths

All statistical differences in the change in volumetric water content (Δθ) at each depth are recorded in Table 2.16. The equation for the change in volumetric water content between growth stages is $\Delta\theta$ GS1-GS2 = $\theta_{gs1} - \theta_{gs2}$, in which θ_{gs1} is the volumetric water content at growth stage 1, and θ_{gs2} is the volumetric water content at growth stage 2 (ie. Δθ Emergence-Maturity= $\theta_{Emergence} - \theta_{Maturity}$). All statistical differences correspond to the graphs in Figure 2.17. Each depth the volumetric water content was determined for, had a water content reading in the middle of that respective depth. Depths of soil profile for depths 1 through 6 were 0 to 30.5 cm, 30.5 to 61.0 cm, 61.0 to 91.4 cm, 91.4 to 121.9 cm, 121.4 to 152.4 cm, and 152.4 to 182.9 cm respectively (depth 6 only used at Tribune and Garden City).

Table 2.16 Significant Differences between Hybrid Means of the Total Change in Soil Profile Volumetric Water Contents throughout the Growing Season for all Environments in 2014 and 2015 at Depths Corresponding to Graphs in Figure 2.17.

Environment	Hybrid	Δθ Emergence-Maturity						Δθ Emergence-Flowering						Δθ Flowering-Maturity					
		D1	D2	D3	D4	D5	D6	D1	D2	D3	D4	D5	D6	D1	D2	D3	D4	D5	D6
GCD14	h2	-	-	-	-	-	-	-	-	A	-	-	-	-	B	-	-	-	-
GCD14	h3	-	-	-	-	-	-	-	-	A	-	-	-	-	AB	-	-	-	-
GCD14	h4	-	-	-	-	-	-	-	-	B	-	-	-	-	A	-	-	-	-
GCD15	h2	-	-	-	-	-	-	-	-	-	-	-	-	-	B	-	-	-	-
GCD15	h3	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-
GCD15	h4	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-
HTC3314	h1	-	-	-	-	-	†	-	-	-	-	B	†	-	-	-	-	-	†
HTC3314	h2	-	-	-	-	-	†	-	-	-	-	A	†	-	-	-	-	-	†
HTC3314	h3	-	-	-	-	-	†	-	-	-	-	B	†	-	-	-	-	-	†
HTC5015	h1	-	-	B	-	-	†	-	-	B	-	-	†	-	-	-	-	-	†

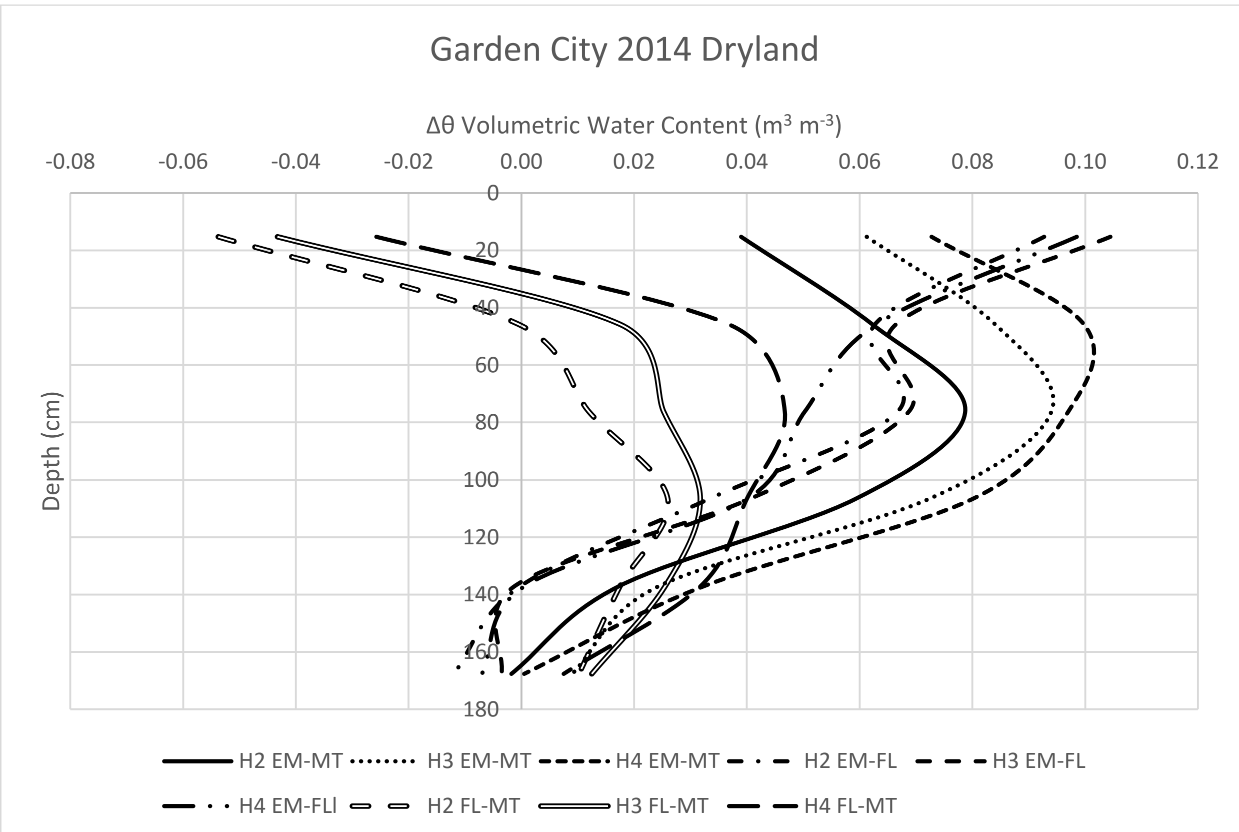
HTC5015	h2	-	-	A	-	-	†	-	-	A	-	-	†	-	-	-	-	-	†
HTC5015	h3	-	-	A	-	-	†	-	-	A	-	-	†	-	-	-	-	-	†
HTC6614	h1	-	-	-	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
HTC6614	h2	-	-	-	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
HTC6614	h3	-	-	-	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
HTCD14	h1	B	-	-	-	-	†	-	-	-	-	-	†	C	-	B	-	-	†
HTCD14	h2	B	-	-	-	-	†	-	-	-	-	-	†	B	-	AB	-	-	†
HTCD14	h3	A	-	-	-	-	†	-	-	-	-	-	†	A	-	A	-	-	†
HTCD15	h1	-	-	A	-	-	†	-	-	-	-	-	†	-	-	-	A	-	†
HTCD15	h2	-	-	B	-	-	†	-	-	-	-	-	†	-	-	-	B	-	†
HTCD15	h3	-	-	A	-	-	†	-	-	-	-	-	†	-	-	-	A	-	†
HTCIr14	h1	-	-	-	-	-	†	-	-	-	-	-	†	-	-	B	-	-	†
HTCIr14	h2	-	-	-	-	-	†	-	-	-	-	-	†	-	-	AB	-	-	†
HTCIr14	h3	-	-	-	-	-	†	-	-	-	-	-	†	-	-	A	-	-	†
HTCIr15	h1	-	-	-	-	-	†	-	-	-	-	-	†	-	AB	-	-	-	†
HTCIr15	h2	-	-	-	-	-	†	-	-	-	-	-	†	-	B	-	-	-	†
HTCIr15	h3	-	-	-	-	-	†	-	-	-	-	-	†	-	A	-	-	-	†
SCAD14	h1	-	-	-	-	-	†	-	-		B	B	†	-	-	-	-	-	†
SCAD14	h2	-	-	-	-	-	†	-	-		A	B	†	-	-	-	-	-	†
SCAD14	h3	-	-	-	-	-	†	-	-		A	A	†	-	-	-	-	-	†
SCAD15	h1	-	-	-	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
SCAD15	h2	-	-	-	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
SCAD15	h3	-	-	-	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
SCAIr14	h1	-	-	-	-	-	†	-	-	-	-	B	†	-	-	-	-	-	†
SCAIr14	h2	-	-	-	-	-	†	-	-	-	-	A	†	-	-	-	-	-	†
SCAIr14	h3	-	-	-	-	-	†	-	-	-	-	AB	†	-	-	-	-	-	†
SCAIr15	h1	-	-	-	-	B	†	-	-	-	-	-	†	-	-	-	-	-	†
SCAIr15	h2	-	-	-	-	A	†	-	-	-	-	-	†	-	-	-	-	-	†
SCAIr15	h3	-	-	-	-	A	†	-	-	-	-	-	†	-	-	-	-	-	†
TOPD14	h1	-	-	A	-	-	†	-	-	A	-	-	†	-	-	-	-	-	†

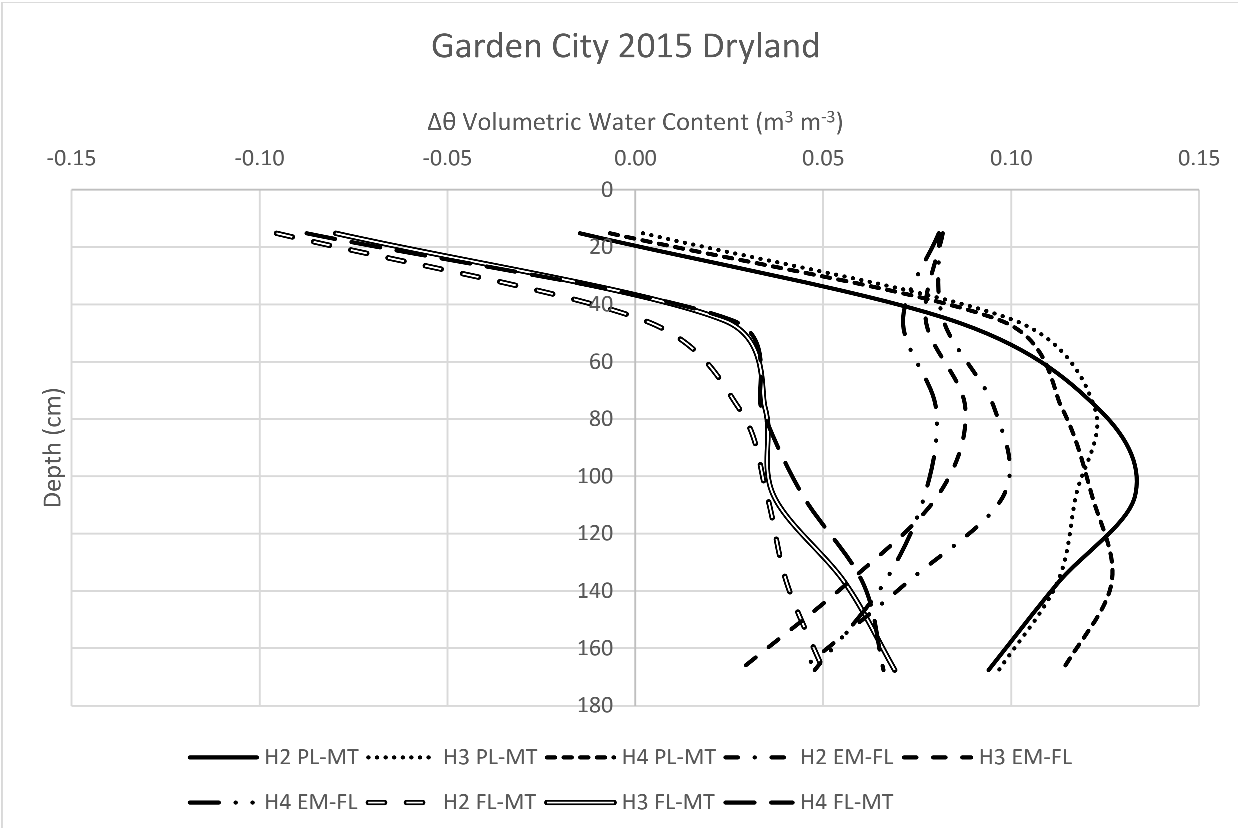
TOPD14	h2	-	-	AB	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
TOPD14	h3	-	-	B	-	-	†	-	-	-	-	-	†	-	-	-	-	-	†
TOPD15	h1	-	-	-	-	-	†	-	-	-	A	B	†	-	-	-	-	-	†
TOPD15	h2	-	-	-	-	-	†	-	-	-	A	A	†	-	-	-	-	-	†
TOPD15	h3	-	-	-	-	-	†	-	-	-	B	B	†	-	-	-	-	-	†
TOPIr14	h1	-	-	A	-	-	†	-	-	-	-	-	†	-	A	-	-	-	†
TOPIr14	h2	-	-	AB	-	-	†	-	-	-	-	-	†	-	B	-	-	-	†
TOPIr14	h3	-	-	B	-	-	†	-	-	-	-	-	†	-	A	-	-	-	†
TOPIr15	h1	-	-	-	-	-	†	-	-	-	-	B	†	-	-	-	-	-	†
TOPIr15	h2	-	-	-	-	-	†	-	-	-	-	A	†	-	-	-	-	-	†
TOPIr15	h3	-	-	-	-	-	†	-	-	-	-	B	†	-	-	-	-	-	†
TRID14	h2	-	-	-	-	A	A	-	-	-	A	A	-	-	A	-	-	-	A
TRID14	h3	-	-	-	-	A	A	-	-	-	A	A	-	-	AB	-	-	-	A
TRID14	h4	-	-	-	-	B	B	-	-	-	B	B	-	-	B	-	-	-	B
TRID15	h2	-	A	-	-	-	-	-	A	-	-	-	-	-	-	-	-	-	-
TRID15	h3	-	A	-	-	-	-	-	A	-	-	-	-	-	-	-	-	-	-
TRID15	h4	-	B	-	-	-	-	-	B	-	-	-	-	-	-	-	-	-	-

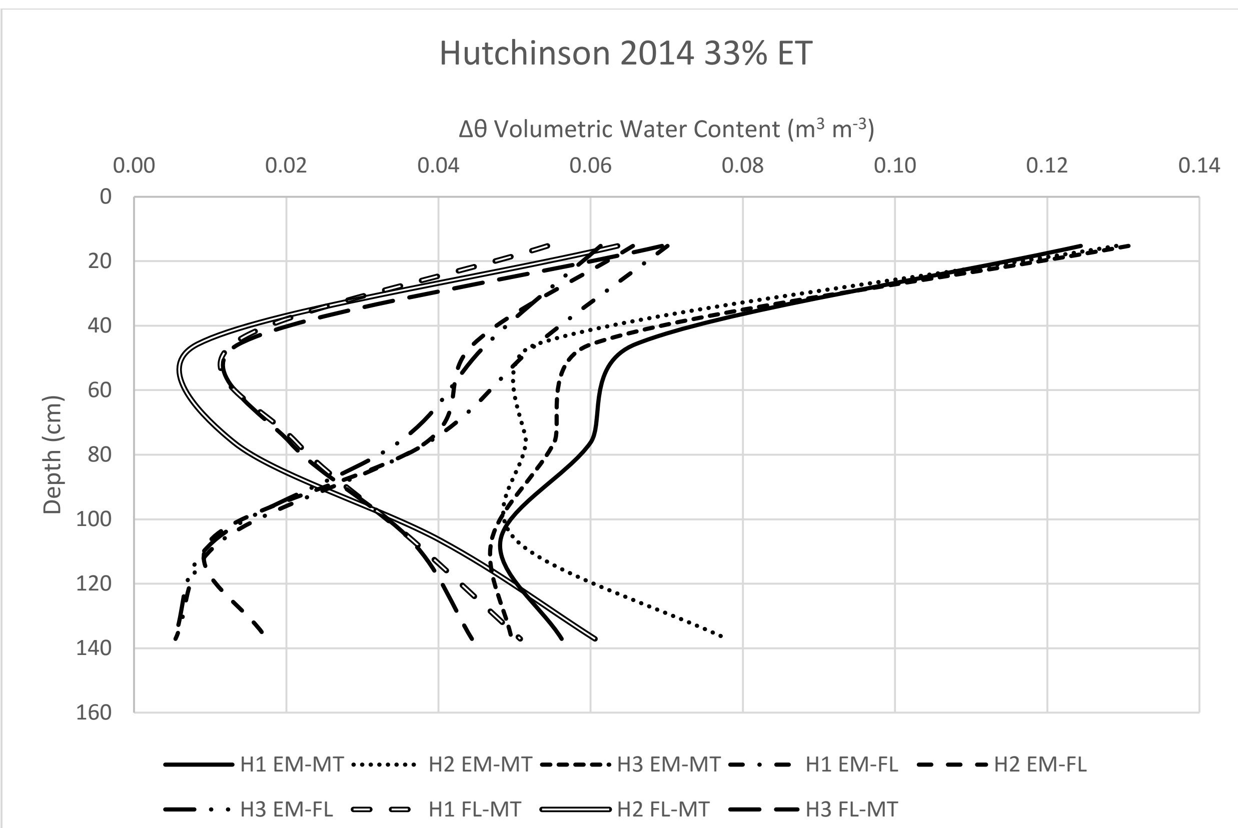
Different letters show significant difference (p-value < 0.05)
- means no significant difference
† Soil moisture content reading not recorded at this depth
D1, D2, D3, D4, D5, and D6 represent depths of soil moisture content readings at 15.2, 45.7, 76.2, 106.7, 137.2, and 167.6 cm respectively
Δθ represents the change in volumetric water content between the physiological stages

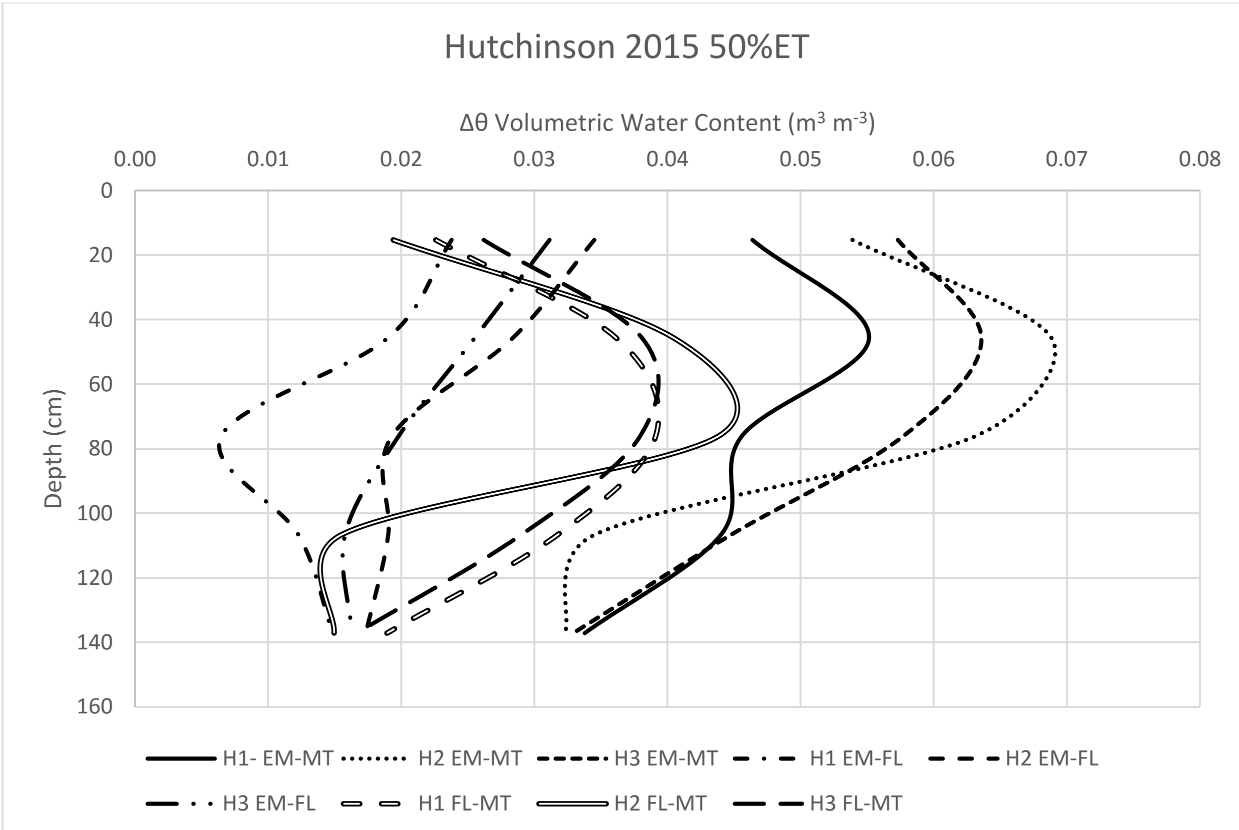
Changes in Volumetric Water Content between Physiological Growth Stages at each Depth

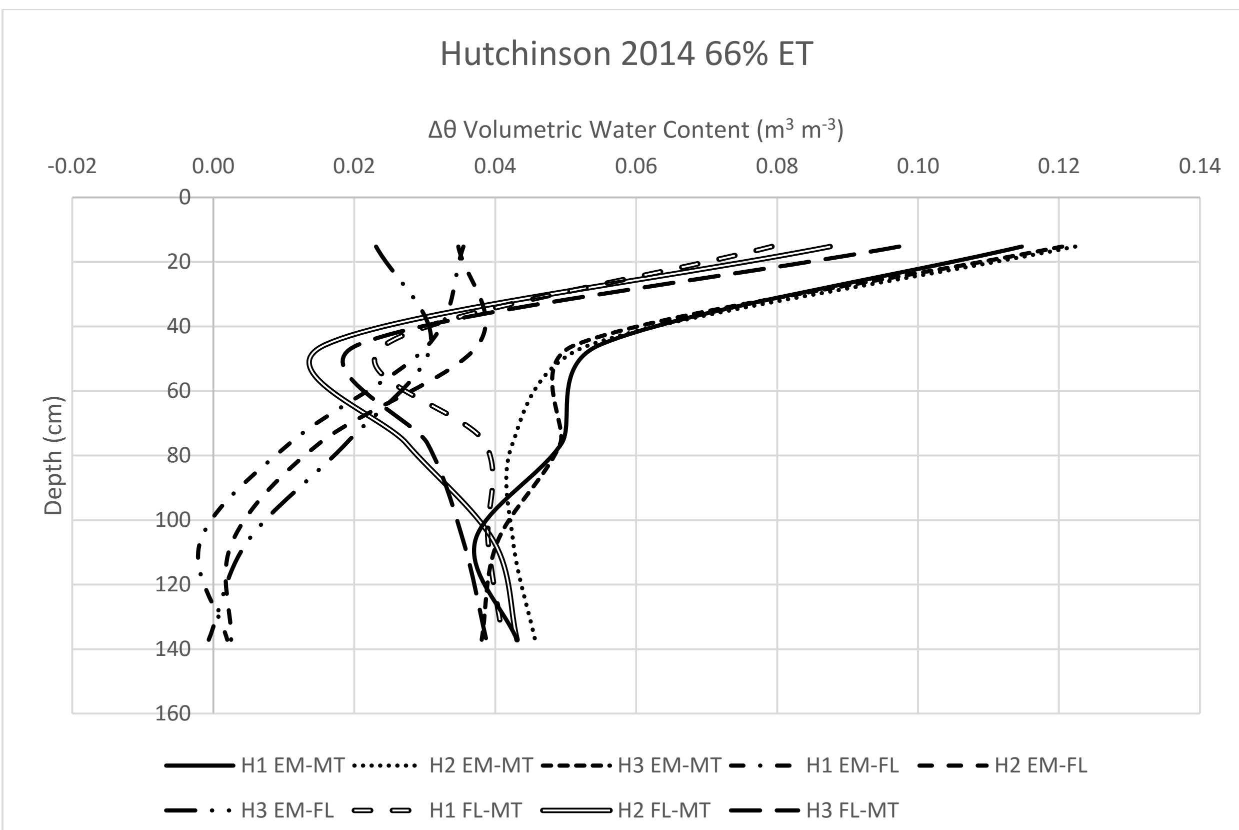
Changes in volumetric water content (Δθ) at each depth represent difference in volumetric water contents between physiological growth stages. A larger difference (values increasing to the right on the x-axis) means that the soil is drier compared relatively to the earlier physiological growth stage. Statistical differences at each depth of soil is shown in Table 2.16 between hybrids with letters. The change in volumetric water content from emergence to maturity will equal the sum of changes in volumetric water content readings from emergence to flowering and flowering to maturity.

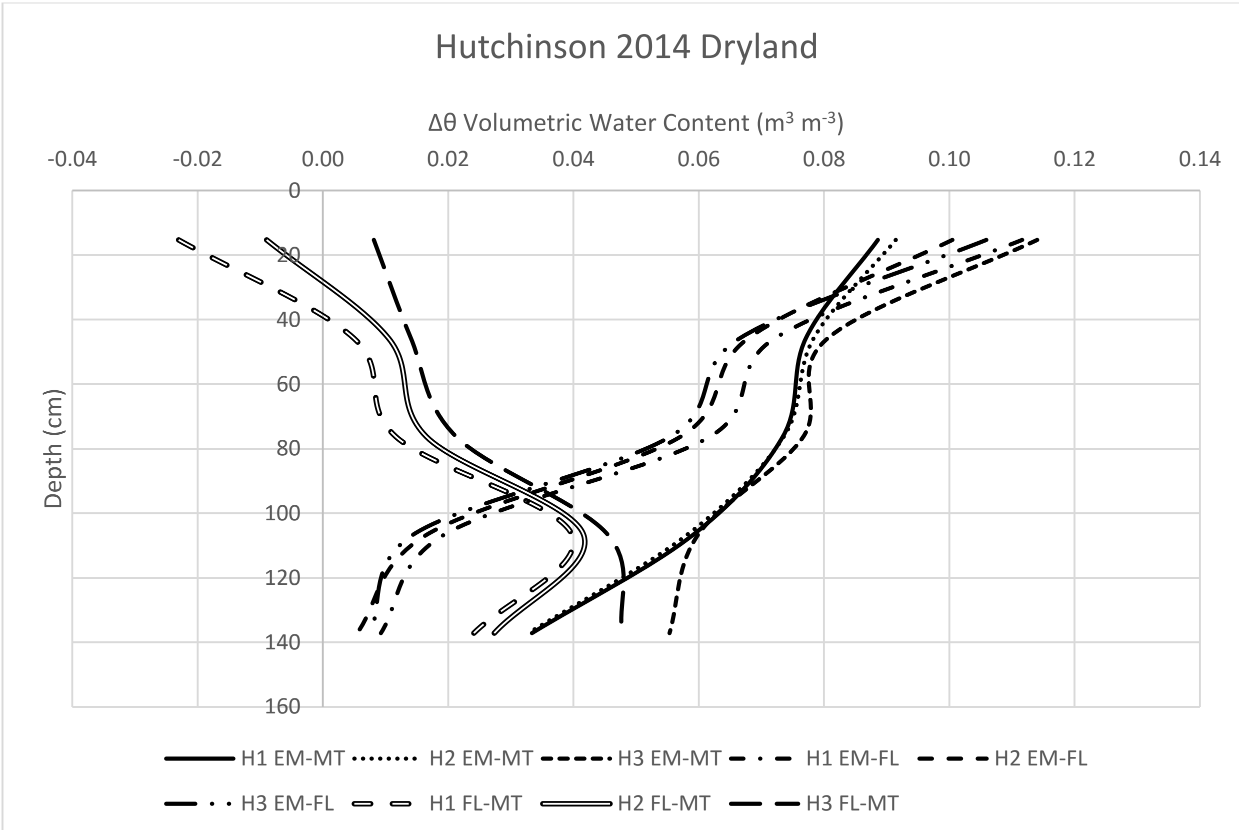


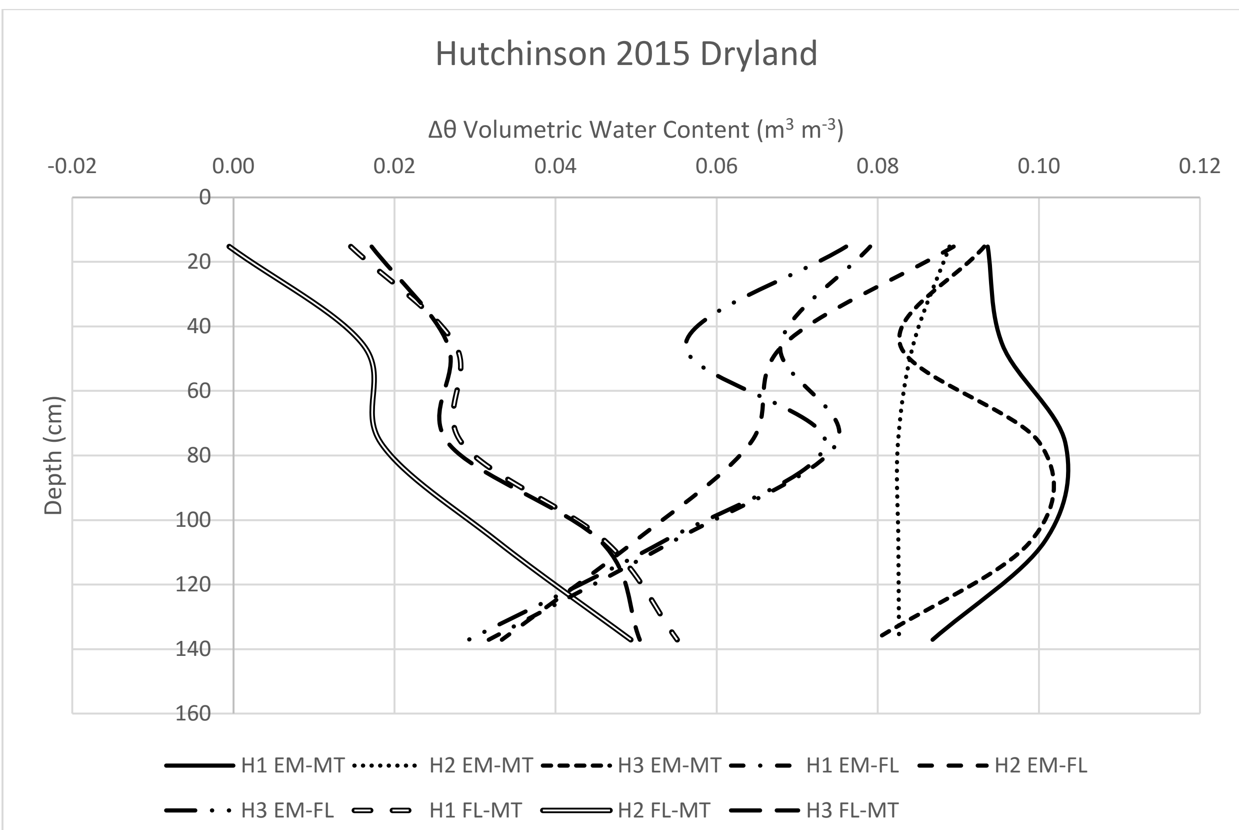

Garden City 2015 Dryland
Δθ Volumetric Water Content (m3 m-3)
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0
20
40
60
80
100
120
140
160
180
Depth (cm)
H2 PL-MT
H3 PL-MT
H4 PL-MT
H2 EM-FL
H3 EM-FL
H4 EM-FL
H2 FL-MT
H3 FL-MT
H4 FL-MT

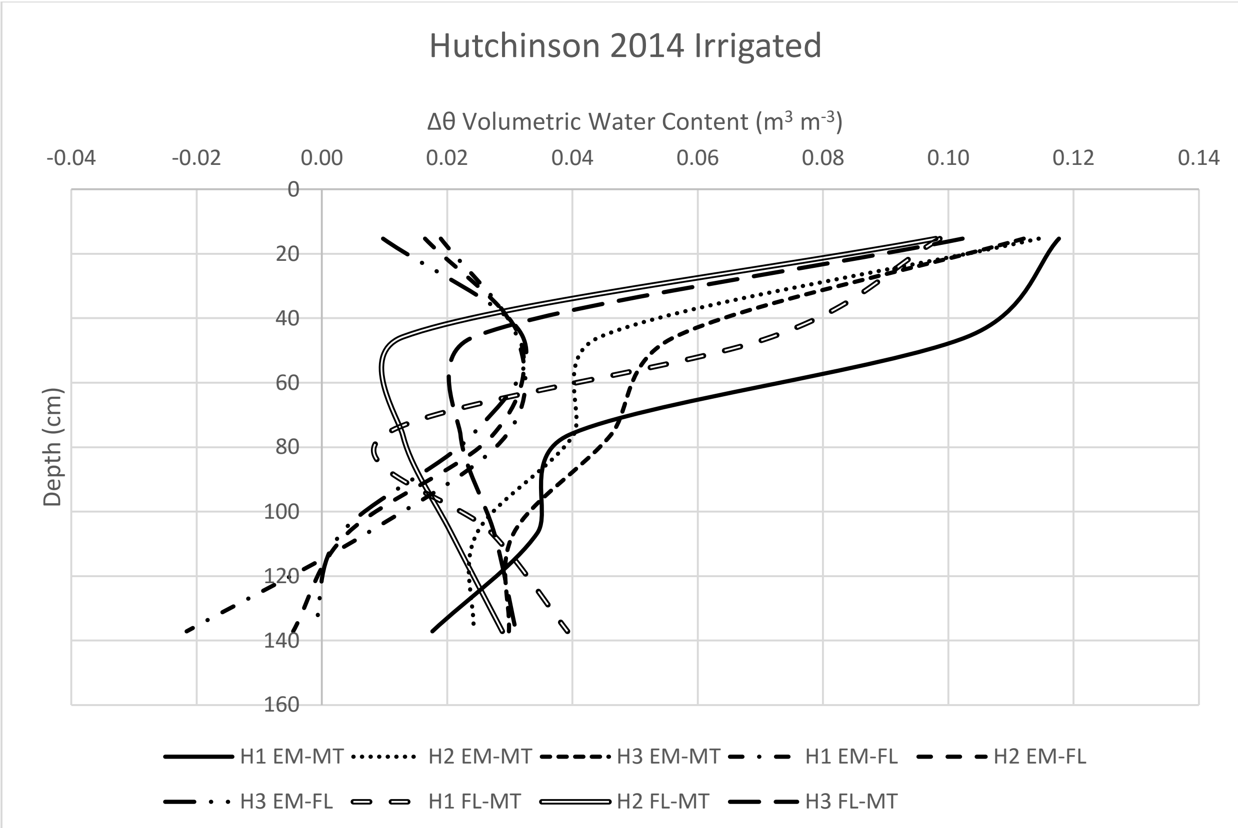

Hutchinson 2014 33% ET
Δθ Volumetric Water Content (m3 m-3)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

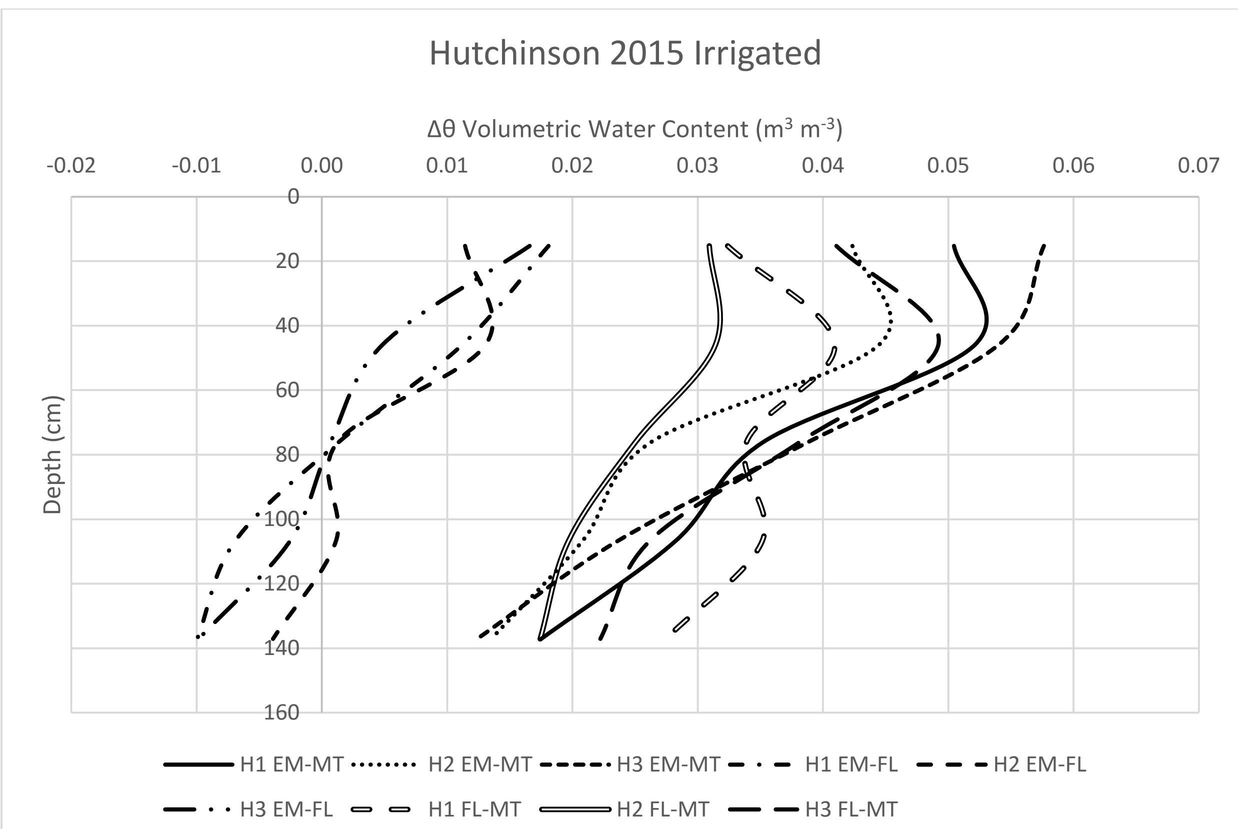

Hutchinson 2015 50%ET
Δθ Volumetric Water Content (m³ m⁻³)
0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
Depth (cm)
0 20 40 60 80 100 120 140 160
H1- EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

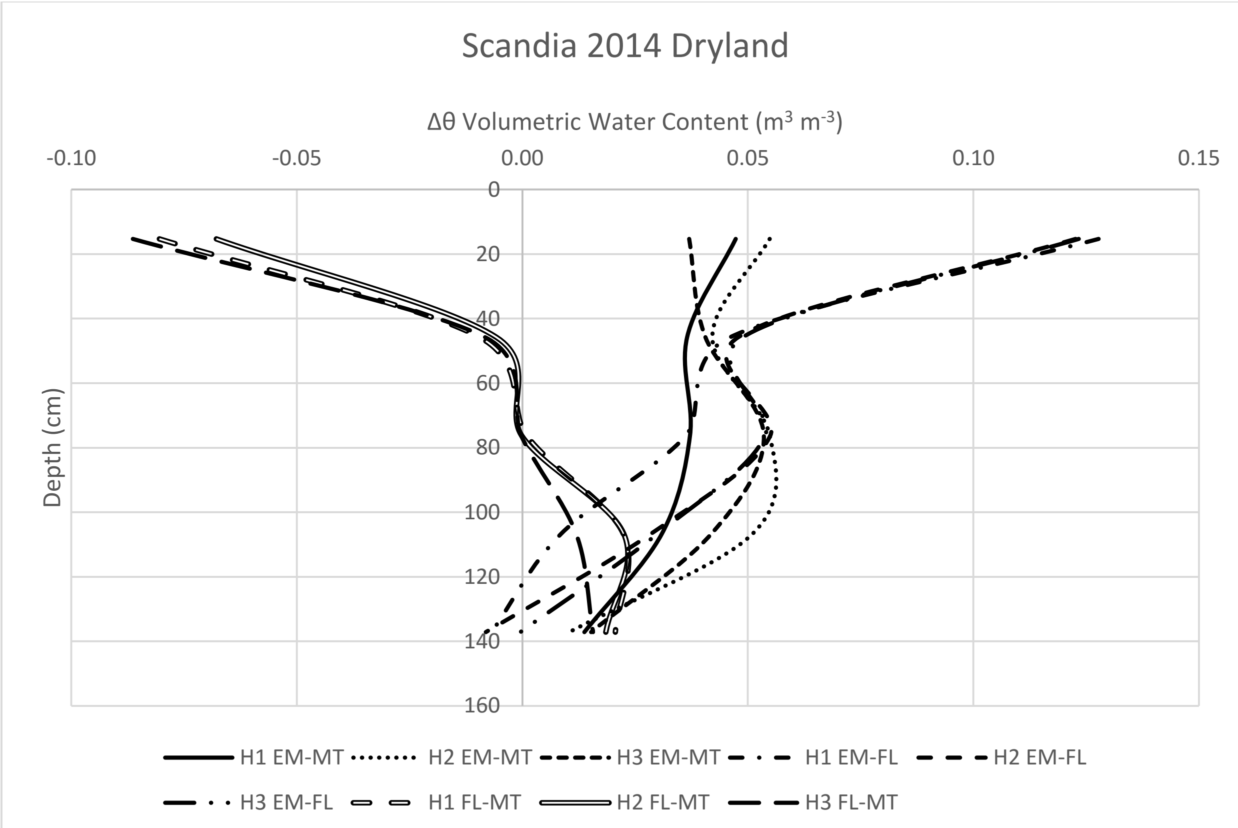

Hutchinson 2014 66% ET
Δθ Volumetric Water Content (m³ m⁻³)
-0.02 0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14
Depth (cm)
0 20 40 60 80 100 120 140 160
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

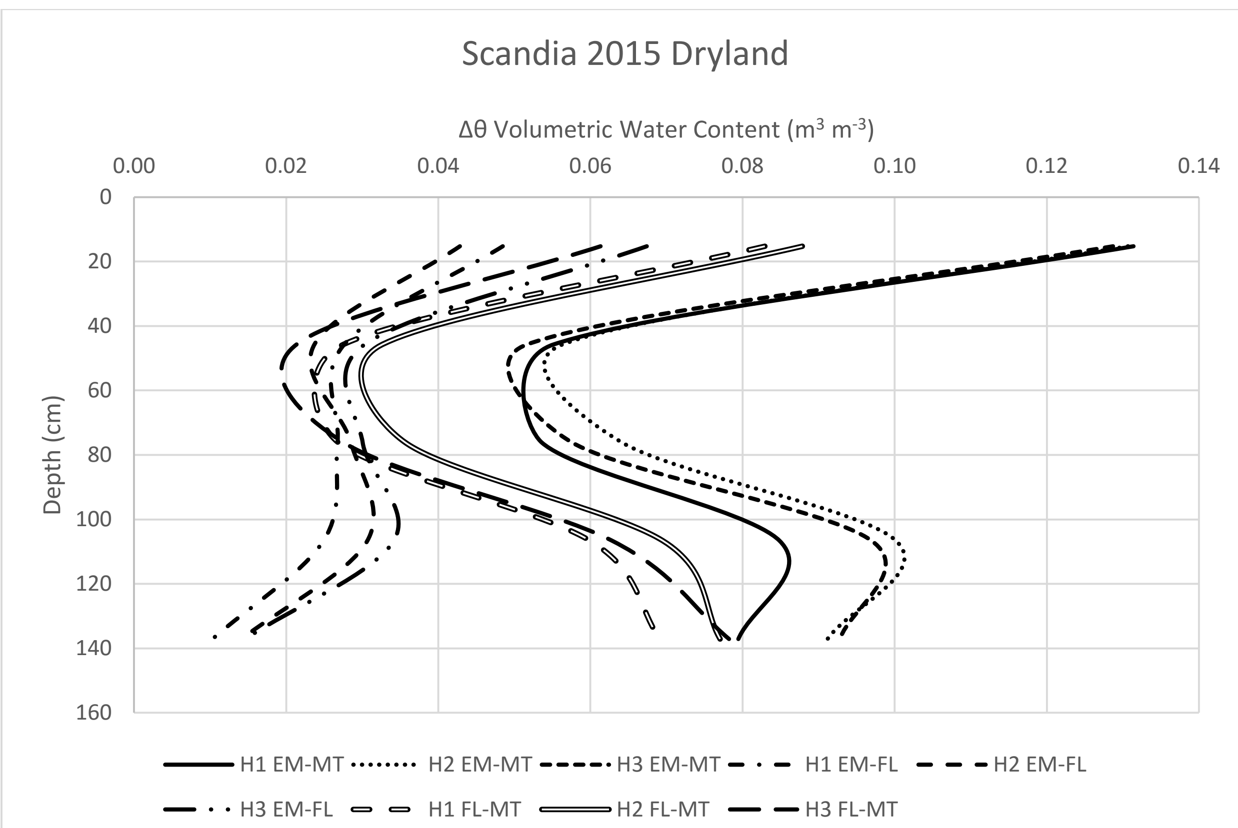

Hutchinson 2014 Dryland
Δθ Volumetric Water Content (m³ m⁻³)
-0.04 -0.02 0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14
Depth (cm)
0 20 40 60 80 100 120 140 160
H1 EM-MT H2 EM-MT H3 EM-MT H1 EM-FL H2 EM-FL
H3 EM-FL H1 FL-MT H2 FL-MT H3 FL-MT

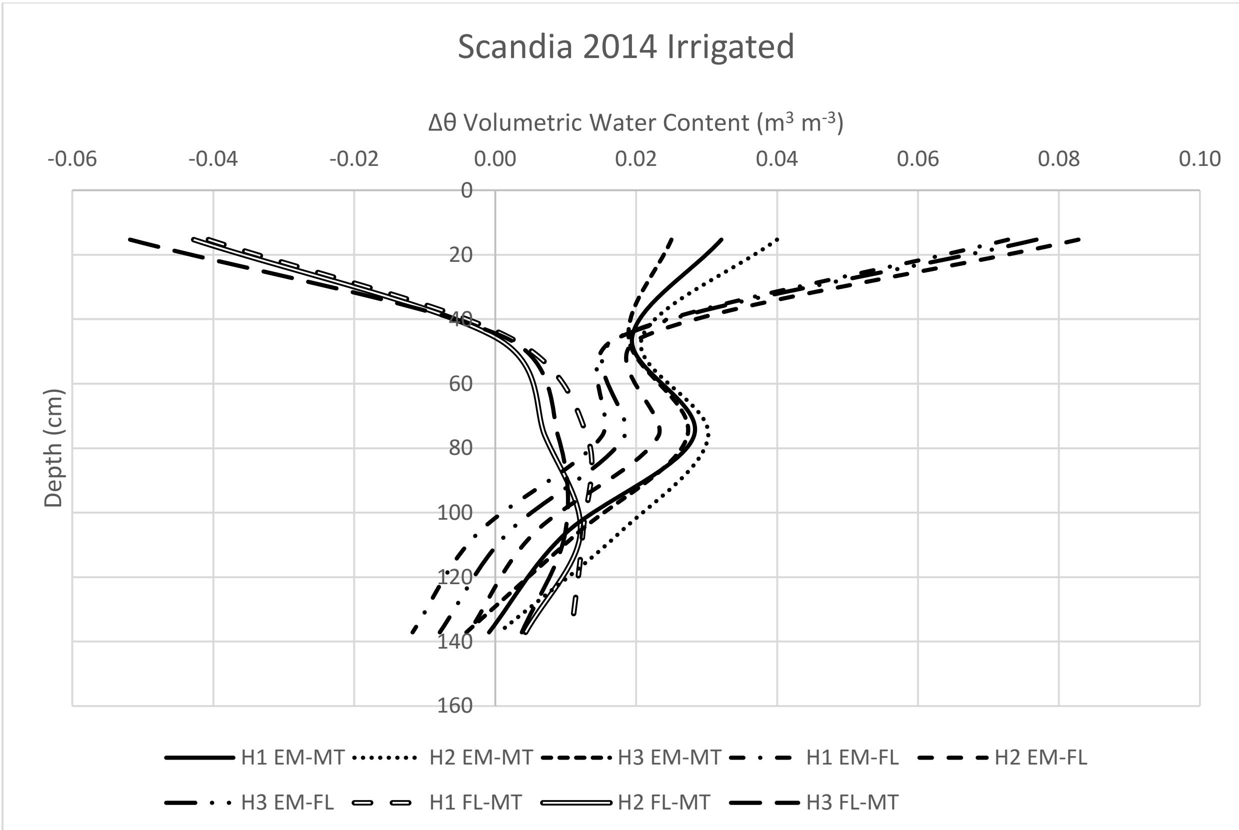

Hutchinson 2015 Dryland
Δθ Volumetric Water Content (m³ m⁻³)
-0.02 0.00 0.02 0.04 0.06 0.08 0.10 0.12
Depth (cm)
0 20 40 60 80 100 120 140 160
H1 EM-MT H2 EM-MT H3 EM-MT H1 EM-FL H2 EM-FL
H3 EM-FL H1 FL-MT H2 FL-MT H3 FL-MT

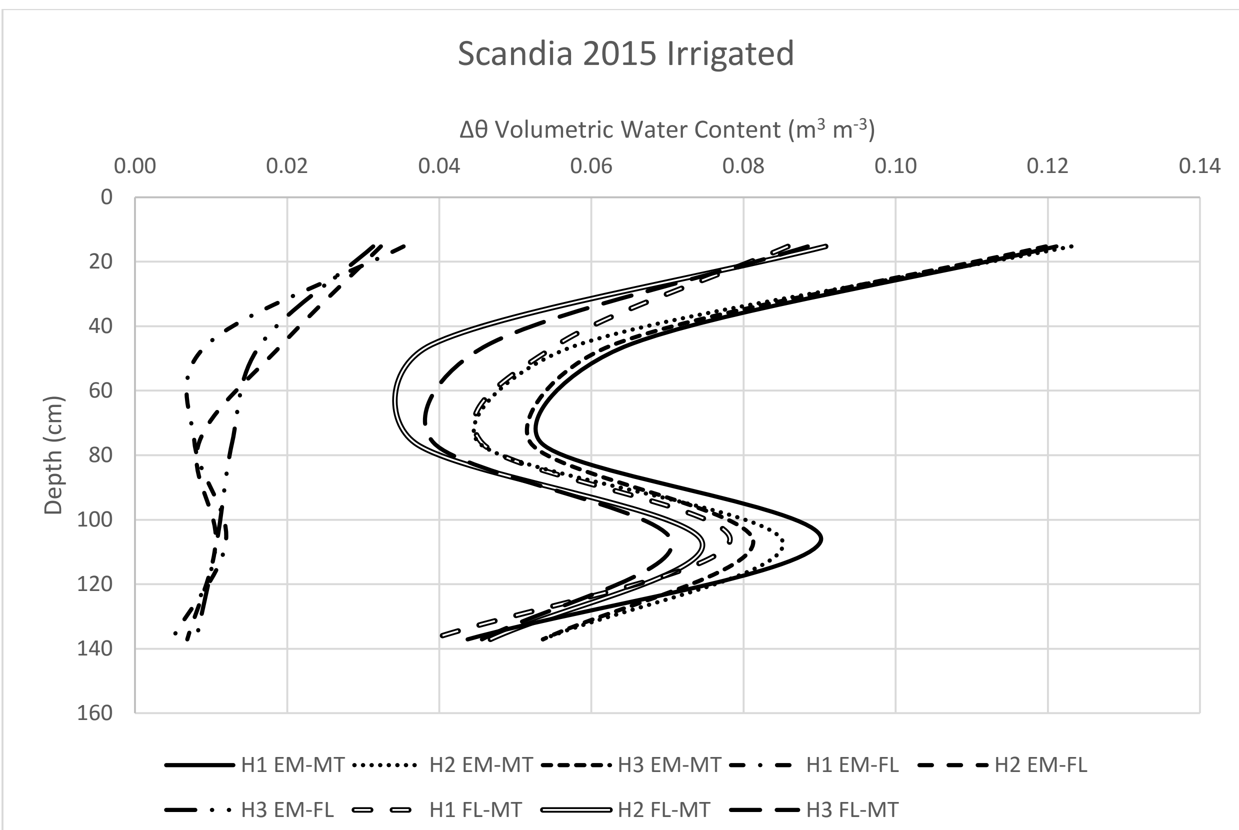

Hutchinson 2014 Irrigated
Δθ Volumetric Water Content (m³ m⁻³)
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Depth (cm)
0
20
40
60
80
100
120
140
160
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

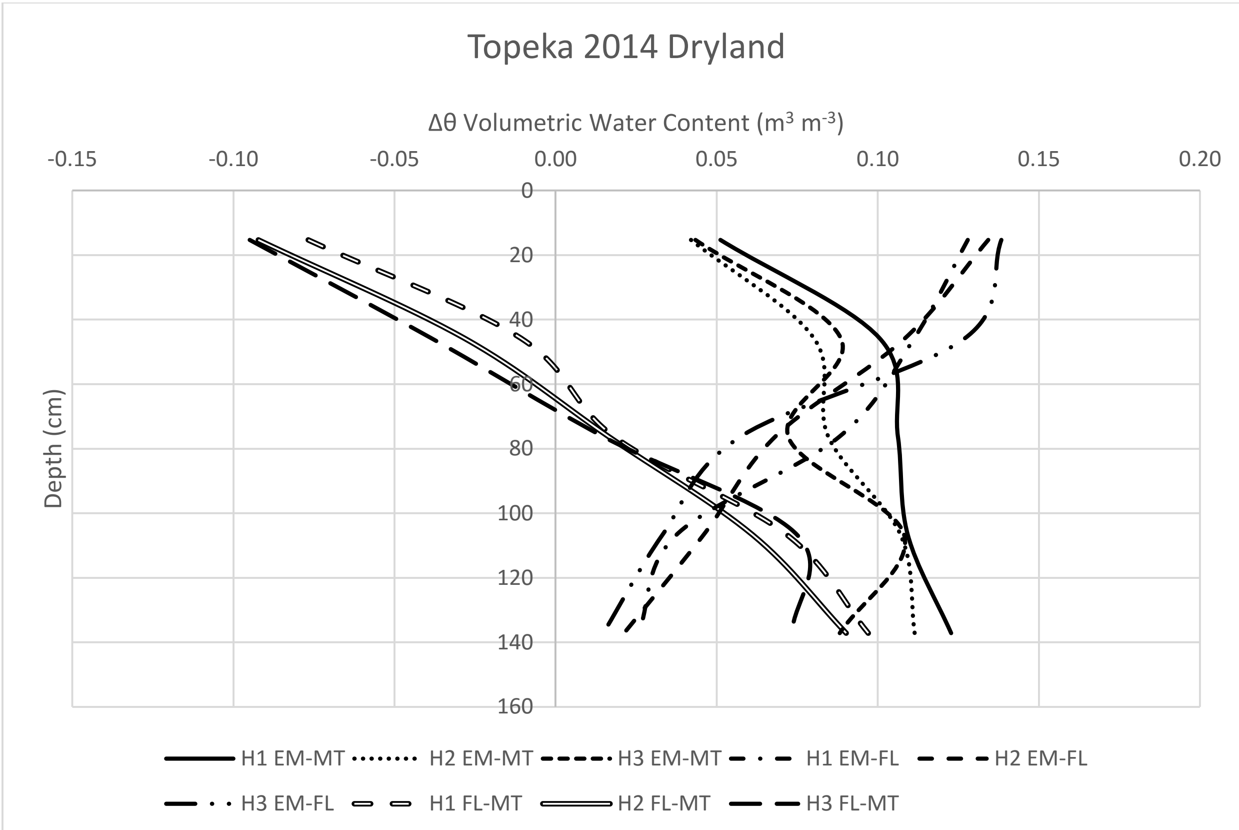

Hutchinson 2015 Irrigated
Δθ Volumetric Water Content (m³ m⁻³)
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Depth (cm)
0
20
40
60
80
100
120
140
160
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

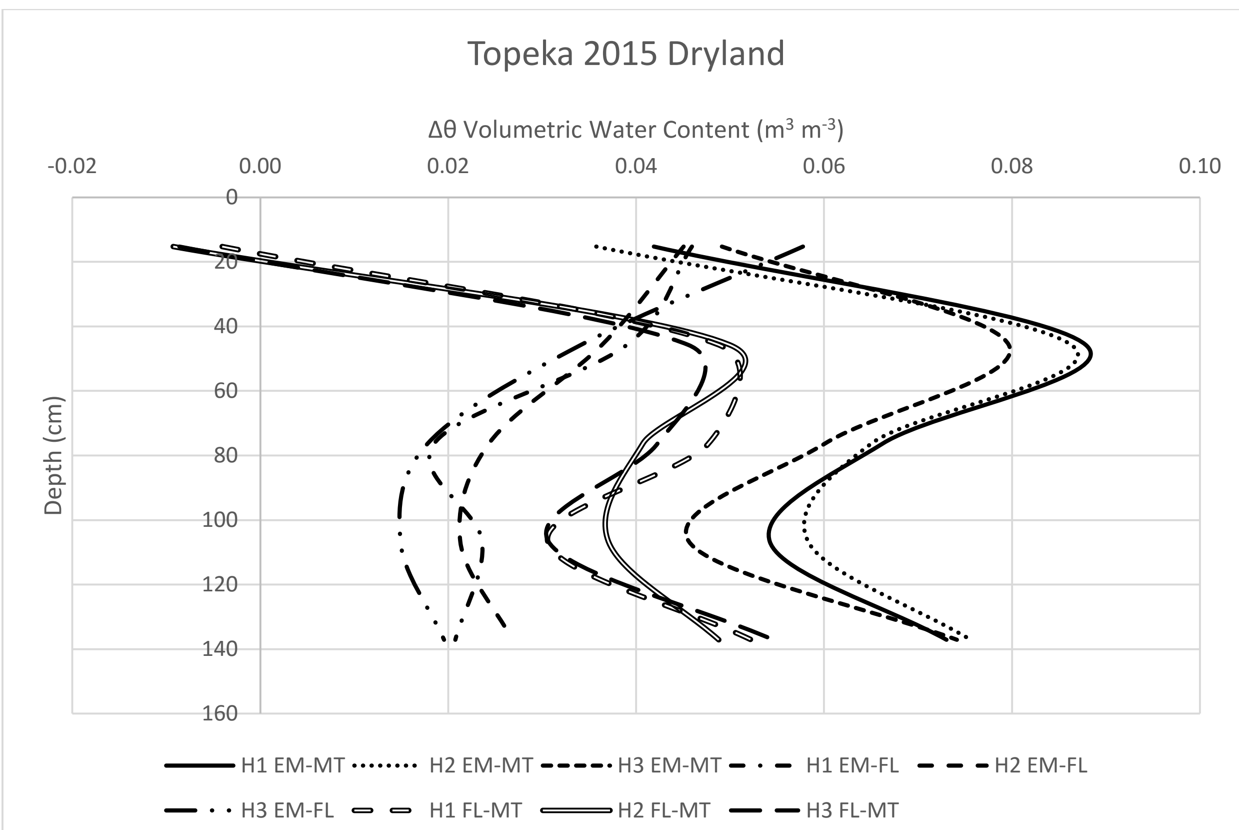

Scandia 2014 Dryland
Δθ Volumetric Water Content (m3 m-3)
-0.10
-0.05
0.00
0.05
0.10
0.15
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

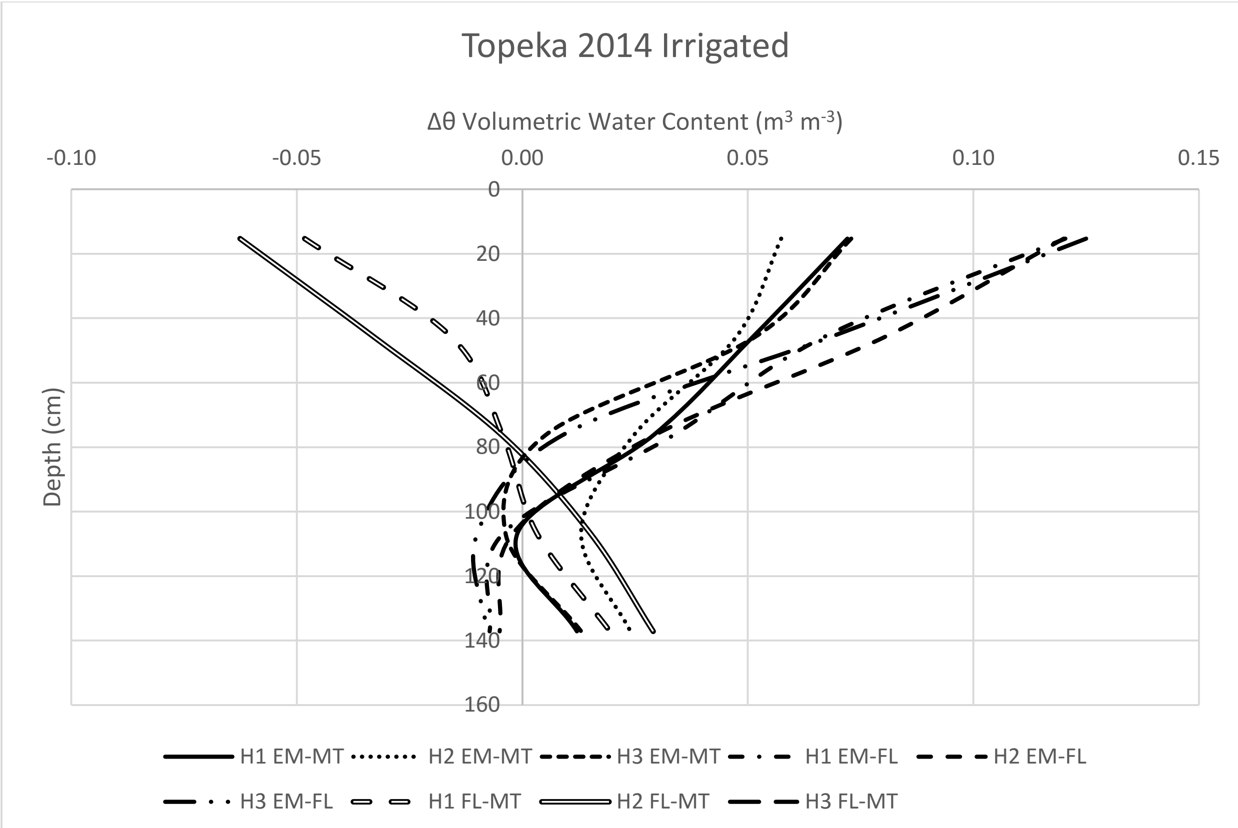

Scandia 2015 Dryland
Δθ Volumetric Water Content (m3 m-3)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT


Scandia 2014 Irrigated
Δθ Volumetric Water Content (m³ m⁻³)
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

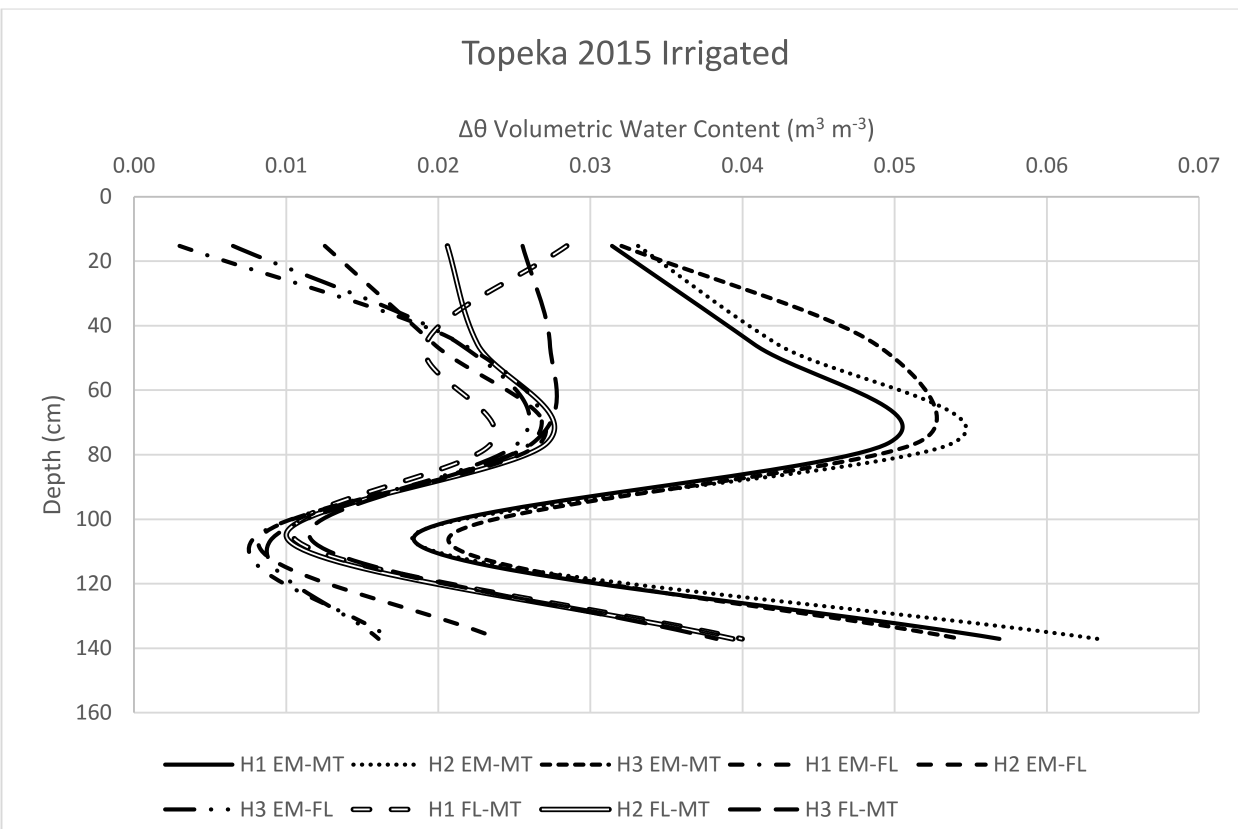

Scandia 2015 Irrigated
Δθ Volumetric Water Content (m³ m⁻³)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT


Topeka 2014 Dryland
Δθ Volumetric Water Content (m3 m-3)
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT

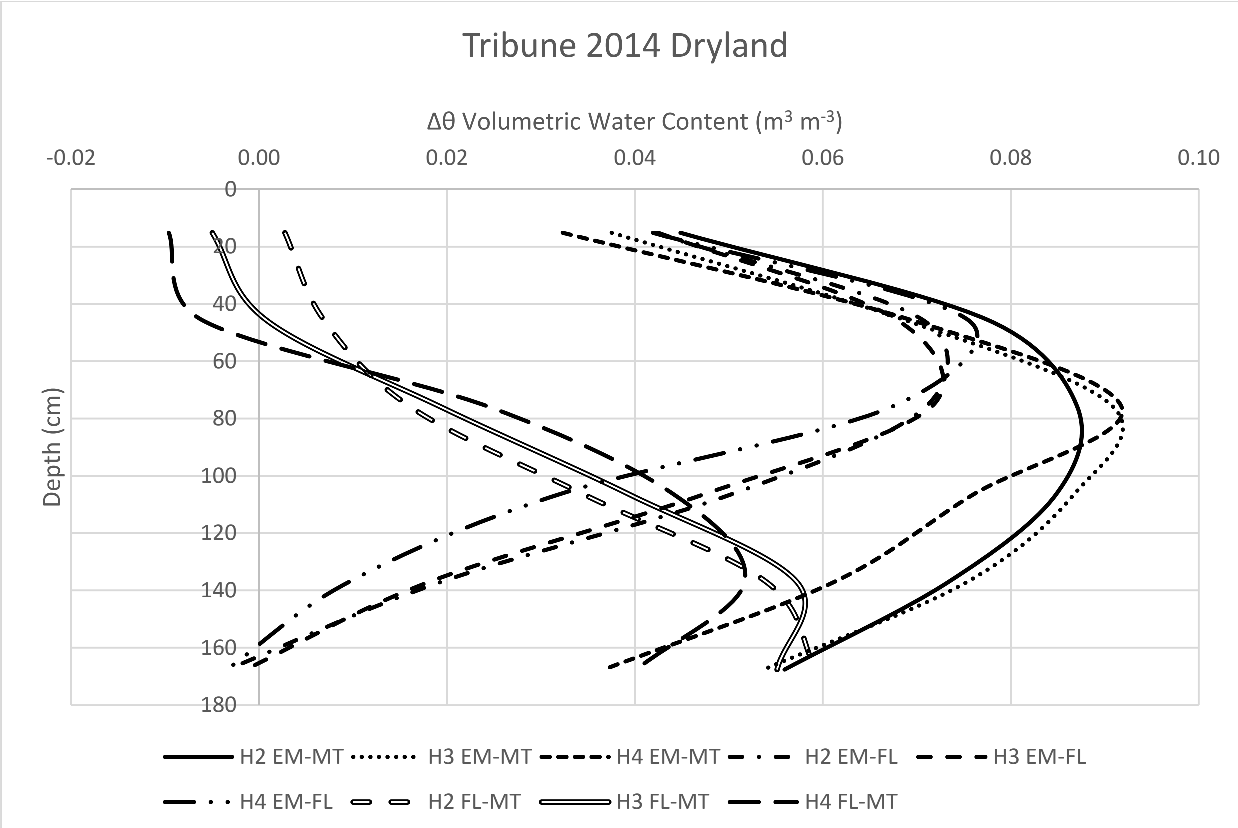

Topeka 2015 Dryland
Δθ Volumetric Water Content (m3 m-3)
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT



Topeka 2014 Irrigated
Δθ Volumetric Water Content (m³ m⁻³)
-0.10
-0.05
0.00
0.05
0.10
0.15
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT



Topeka 2015 Irrigated
Δθ Volumetric Water Content (m³ m⁻³)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0
20
40
60
80
100
120
140
160
Depth (cm)
H1 EM-MT
H2 EM-MT
H3 EM-MT
H1 EM-FL
H2 EM-FL
H3 EM-FL
H1 FL-MT
H2 FL-MT
H3 FL-MT


Tribune 2014 Dryland
Δθ Volumetric Water Content (m3 m-3)
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
Depth (cm)
0
20
40
60
80
100
120
140
160
180
H2 EM-MT
H3 EM-MT
H4 EM-MT
H2 EM-FL
H3 EM-FL
H4 EM-FL
H2 FL-MT
H3 FL-MT
H4 FL-MT

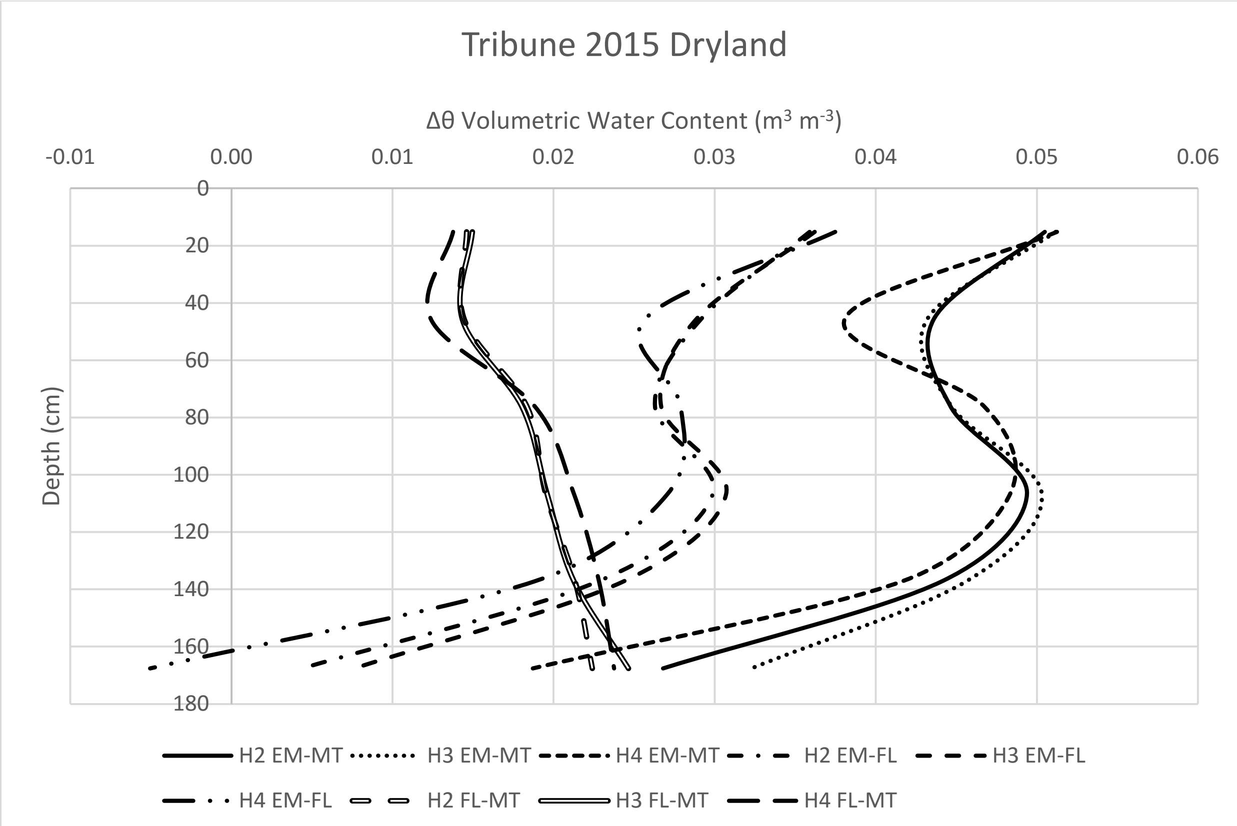
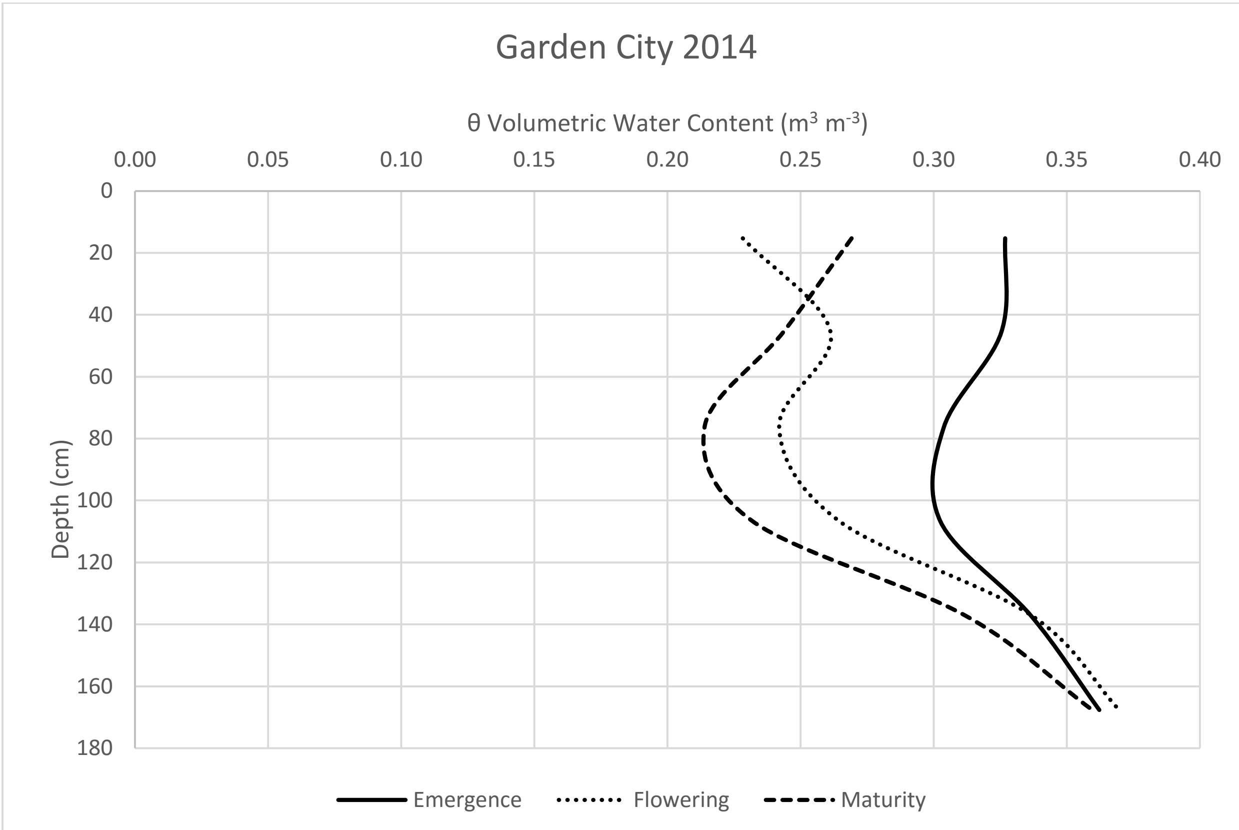
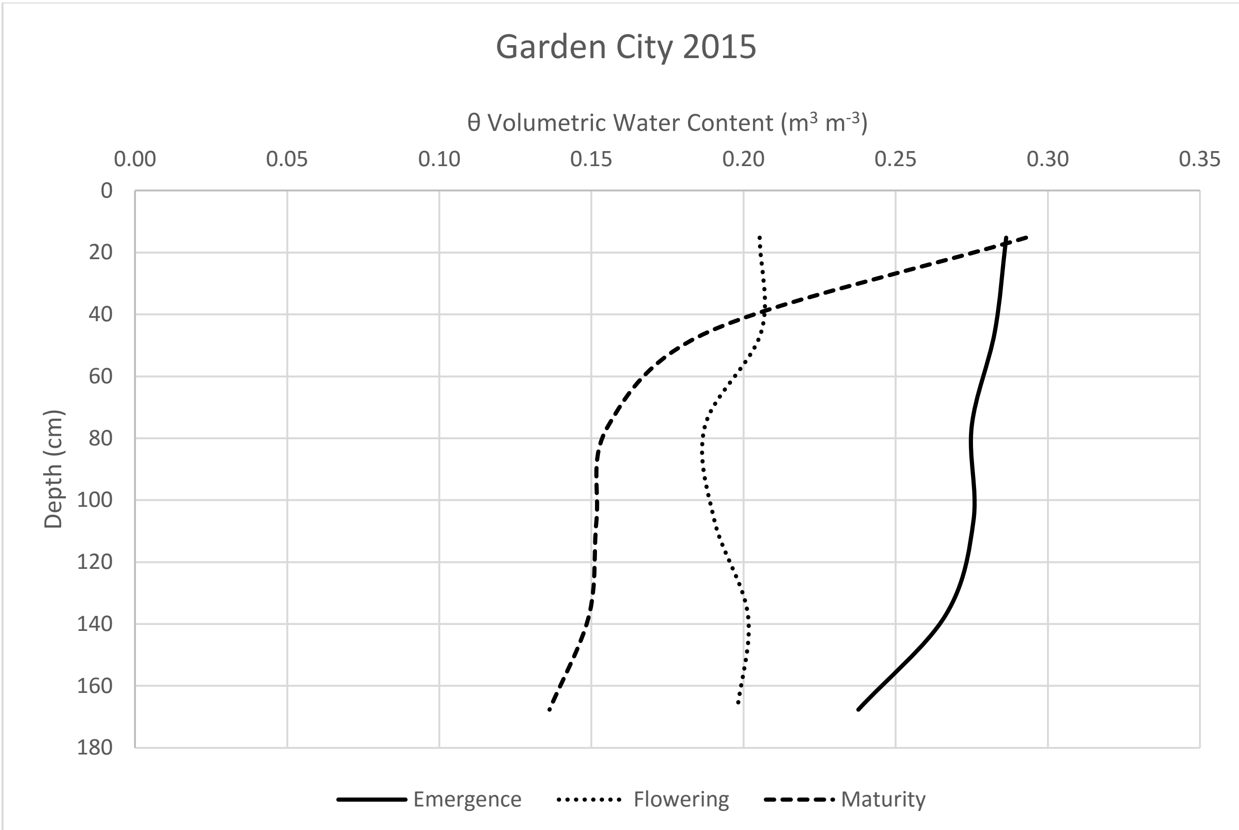
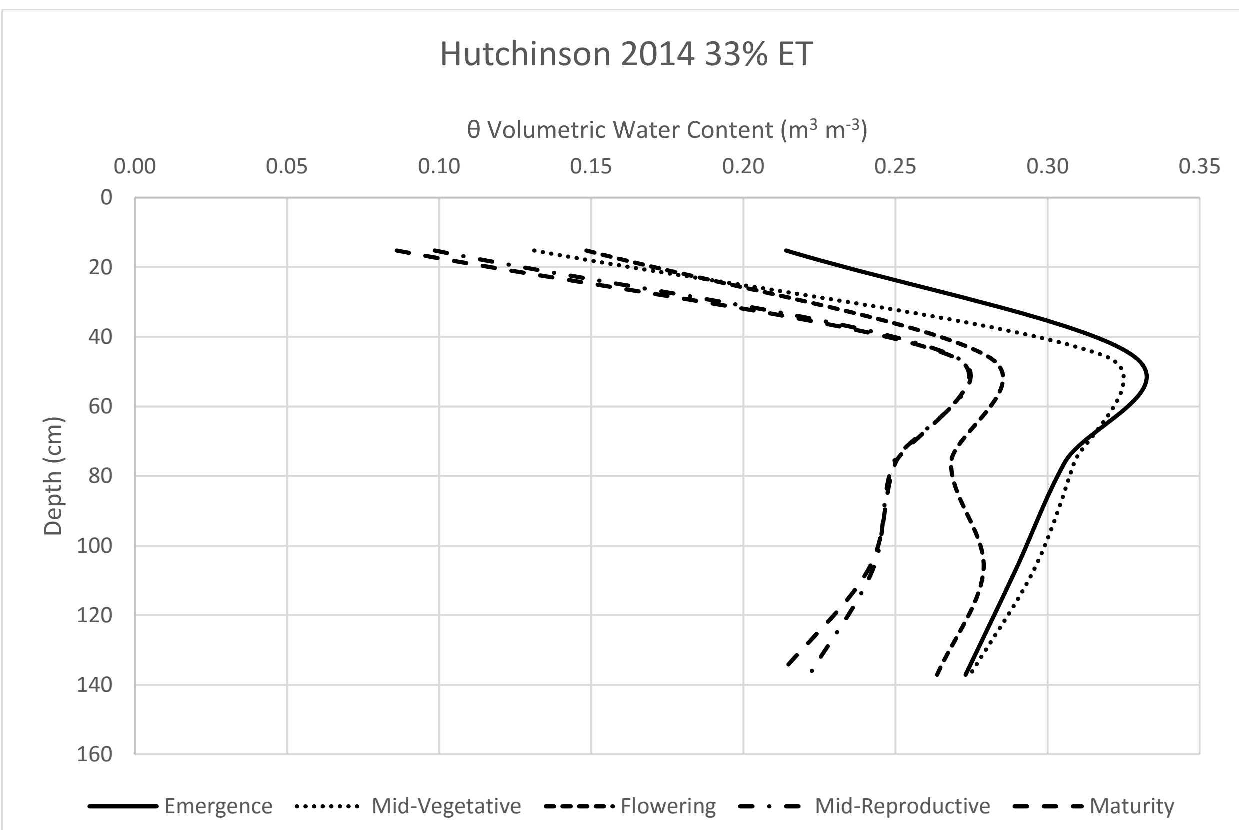


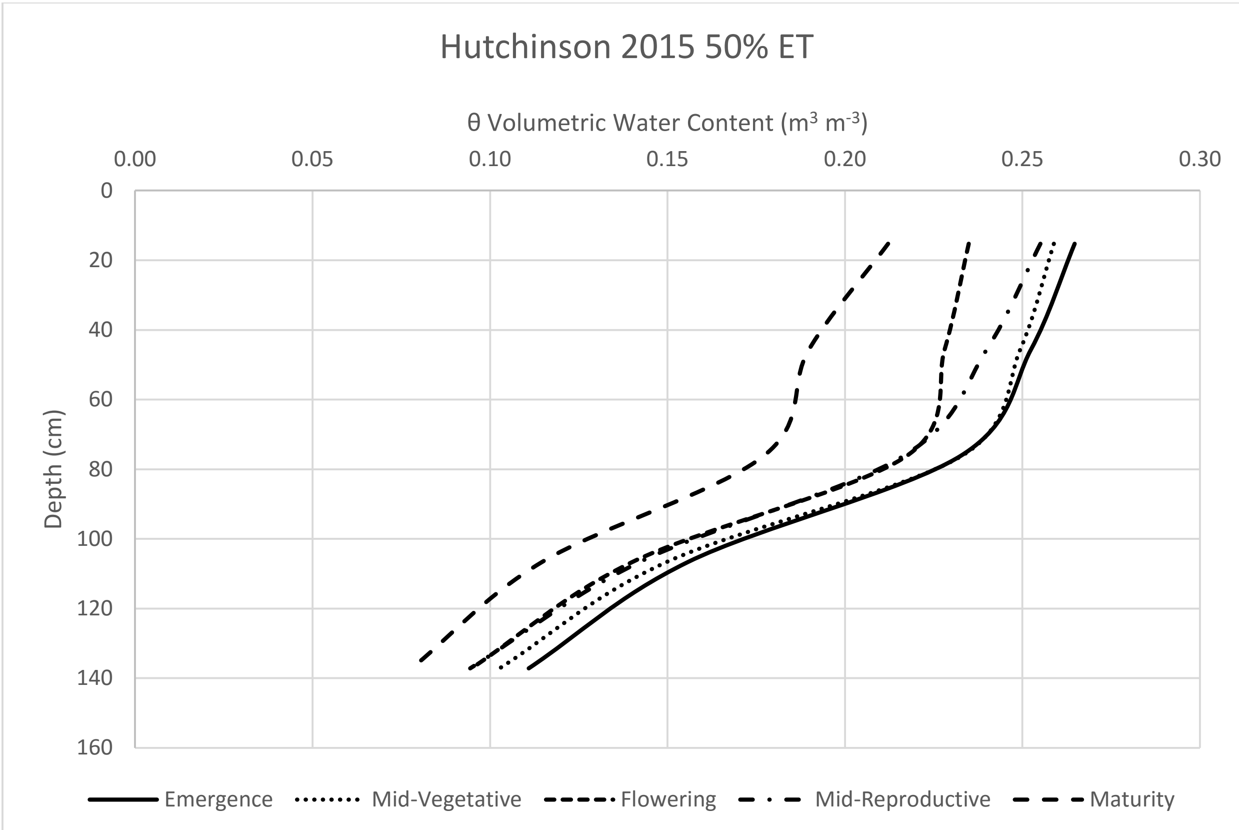
Figure 2.17 Changes in Volumetric Water Contents between Physiological Growth Stages throughout Soil Profile for the Different Hybrids in all Environments in 2014 and 2015.

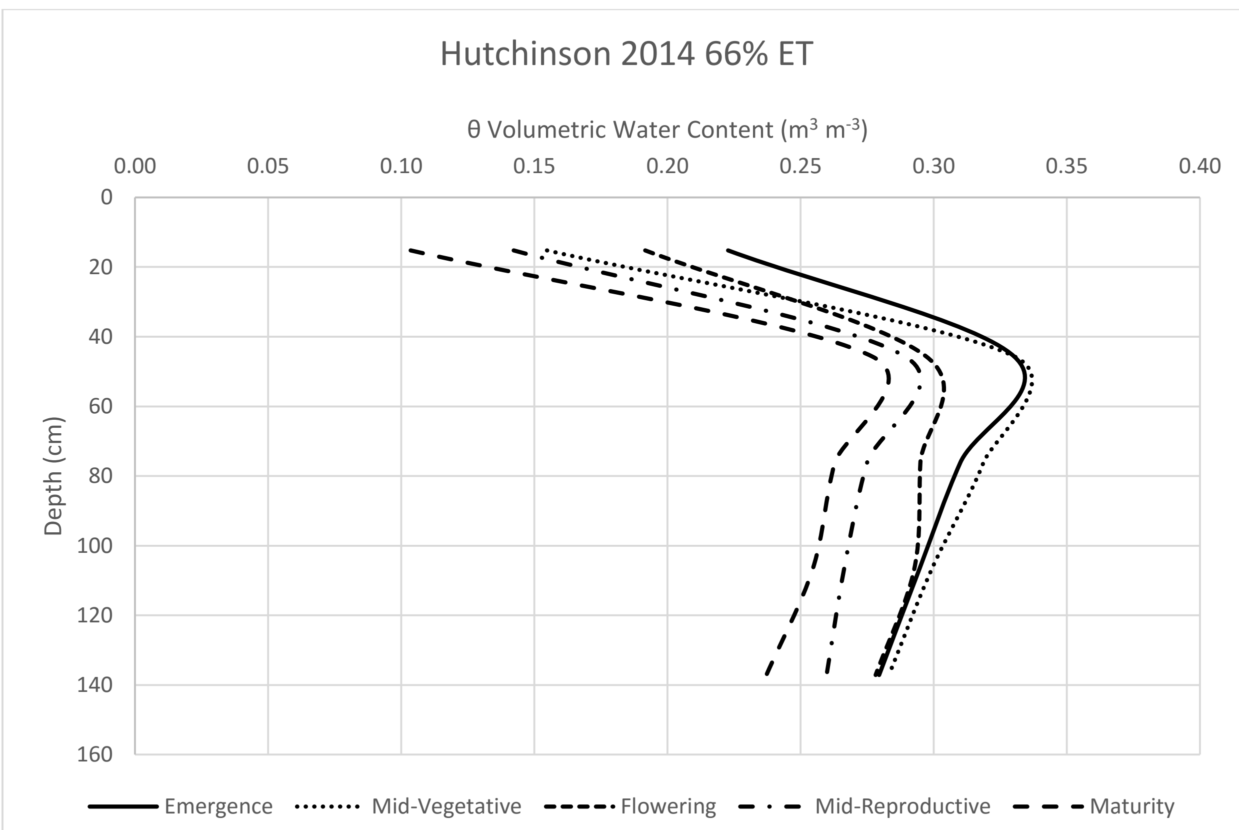
Volumetric Water Contents of Soil Profile at Different Physiological Stages

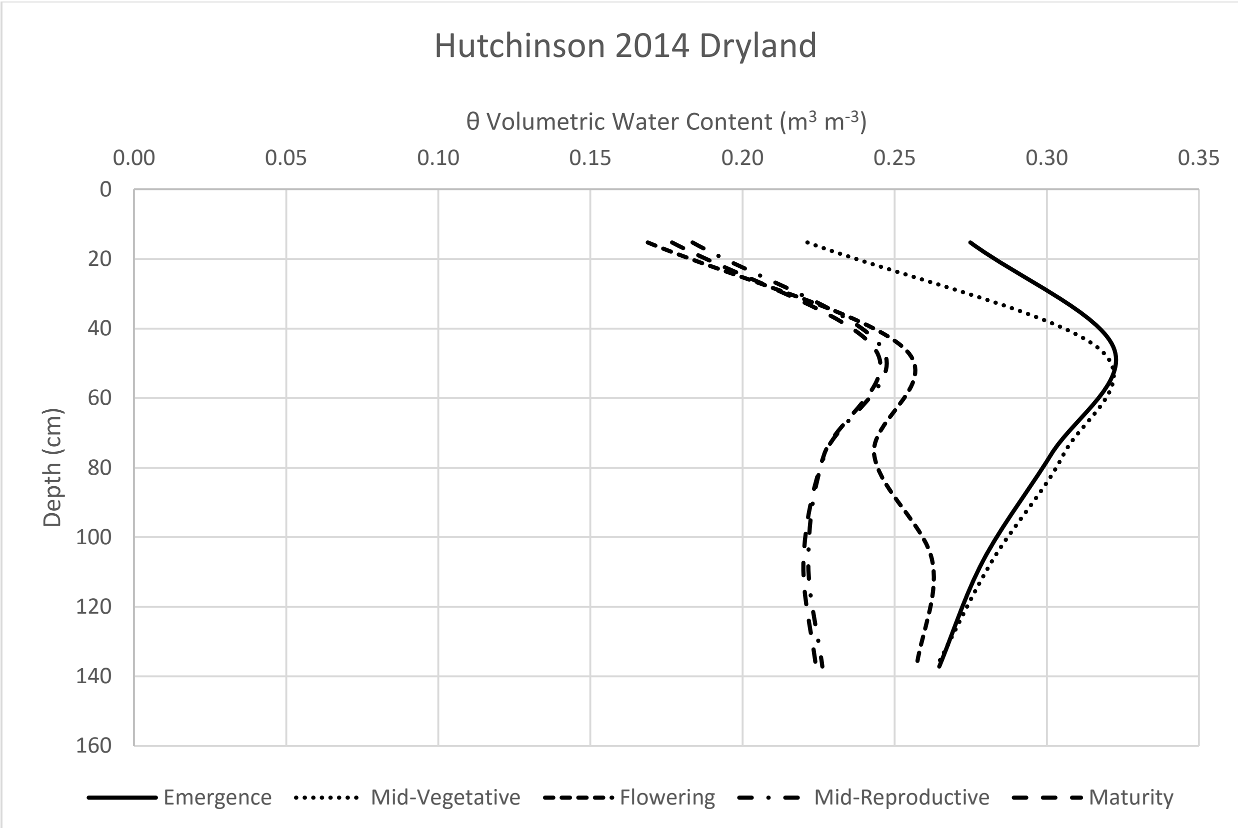


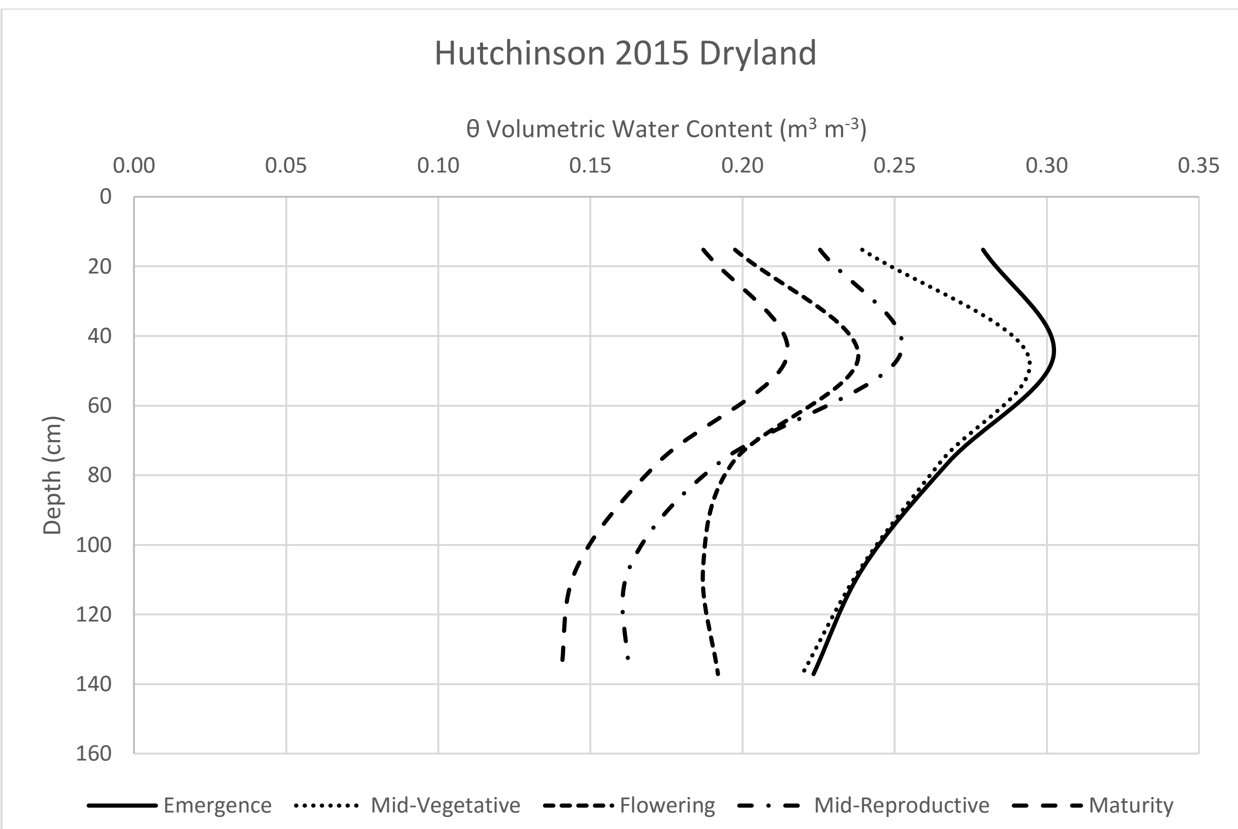

Garden City 2015
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
20
40
60
80
100
120
140
160
180
Depth (cm)
Emergence
Flowering
Maturity

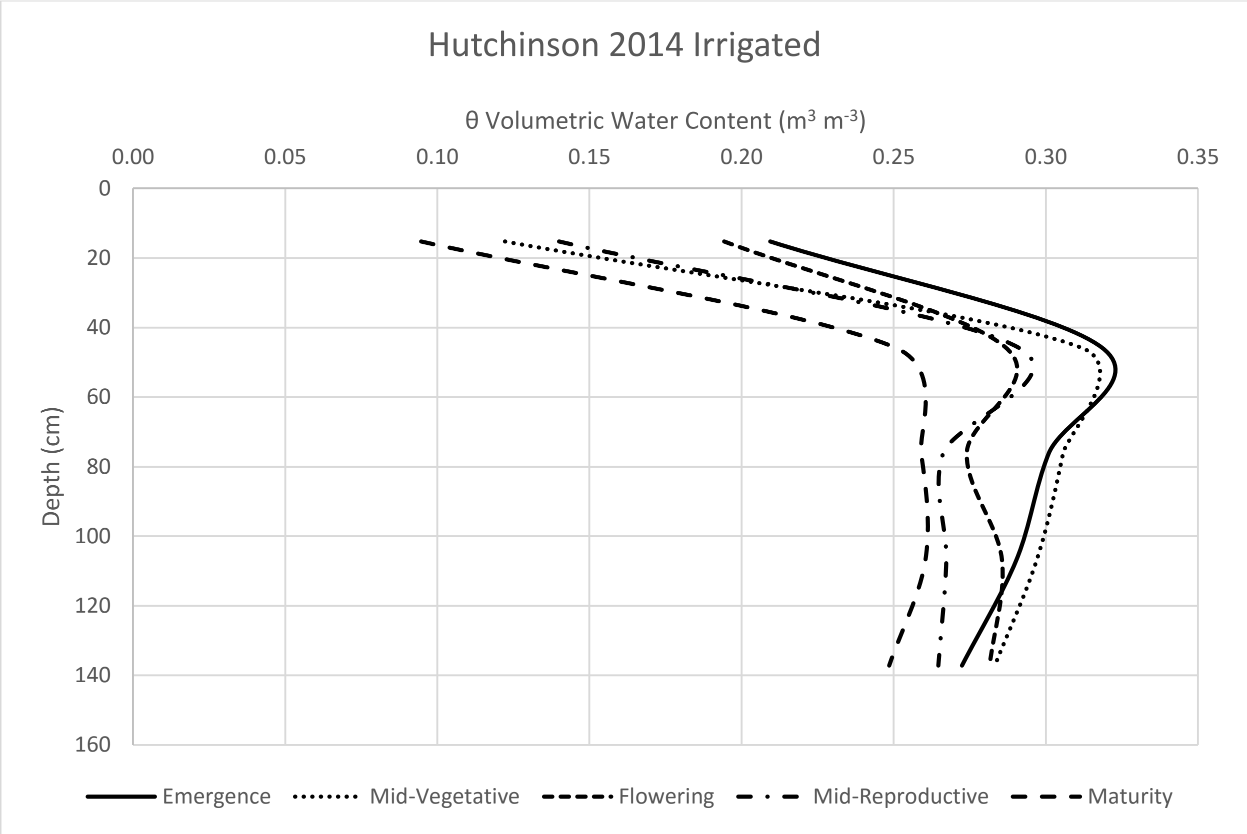

Hutchinson 2014 33% ET
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
20
40
60
80
100
120
140
160
Depth (cm)
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Hutchinson 2015 50% ET
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Depth (cm)
0
20
40
60
80
100
120
140
160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

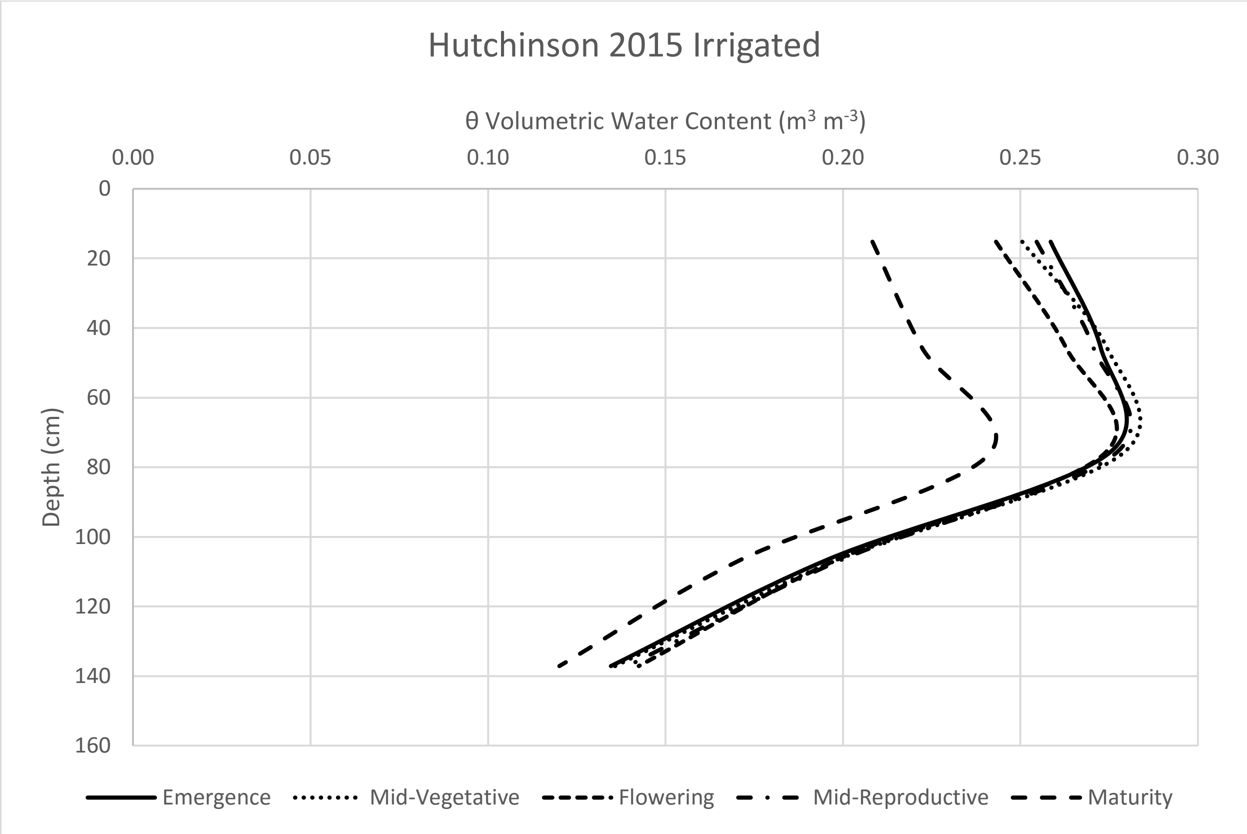

Hutchinson 2014 66% ET
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Depth (cm)
0
20
40
60
80
100
120
140
160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Hutchinson 2014 Dryland
θ Volumetric Water Content (m³ m⁻³)
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
Depth (cm)
0 20 40 60 80 100 120 140 160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

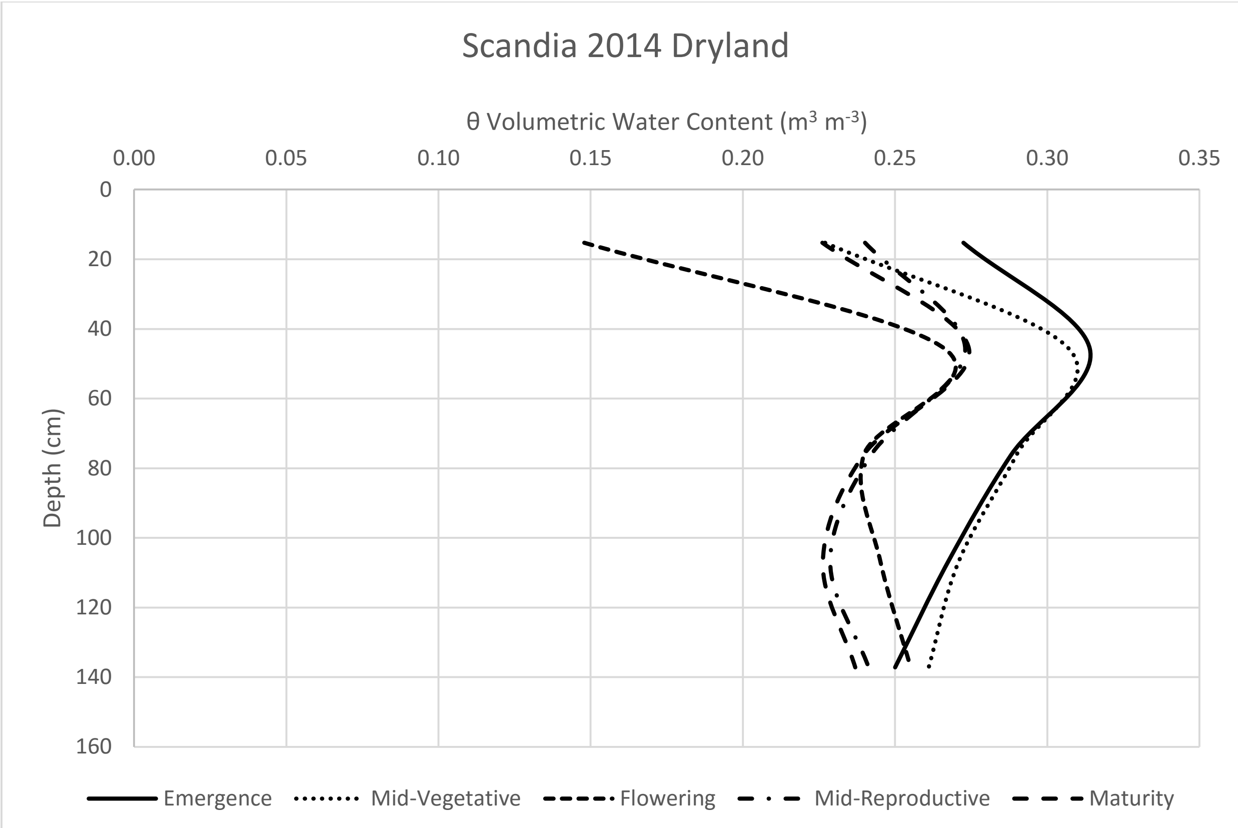

Hutchinson 2015 Dryland
θ Volumetric Water Content (m³ m⁻³)
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
Depth (cm)
0 20 40 60 80 100 120 140 160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

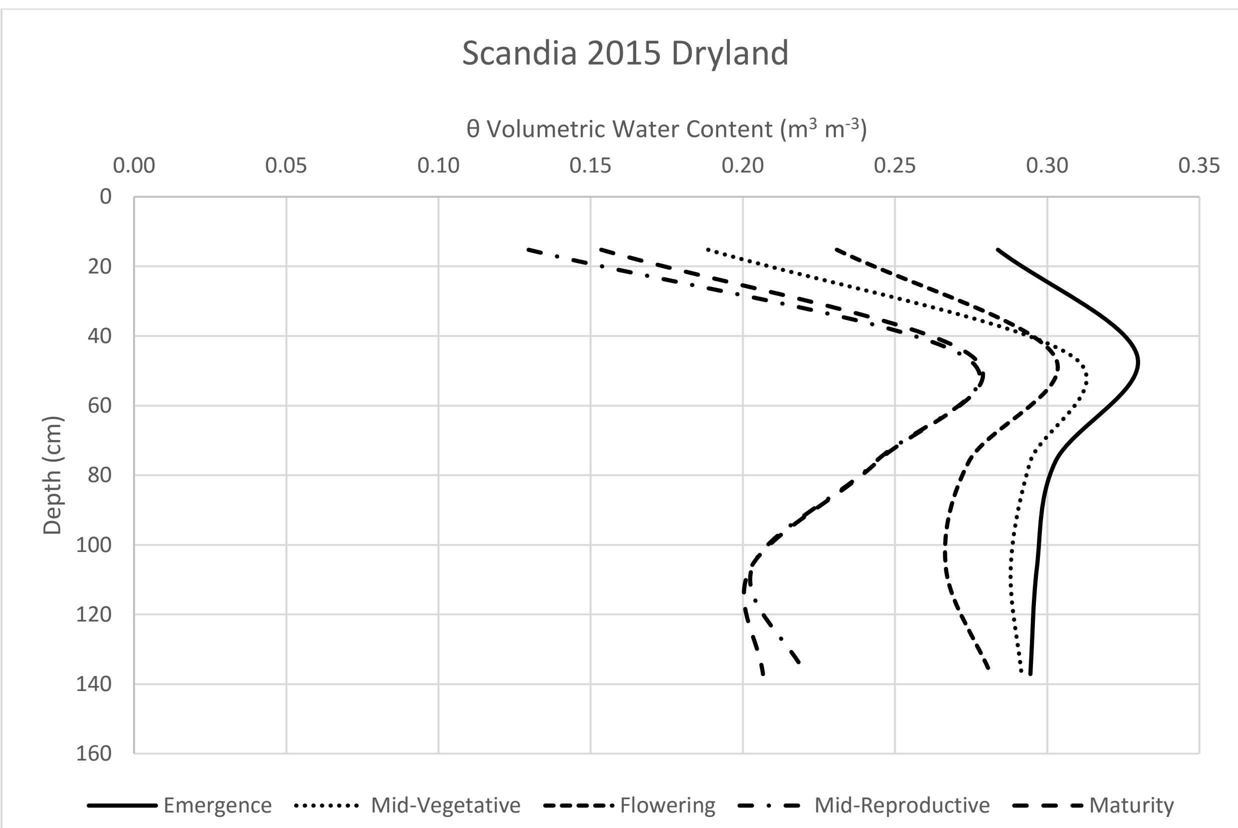


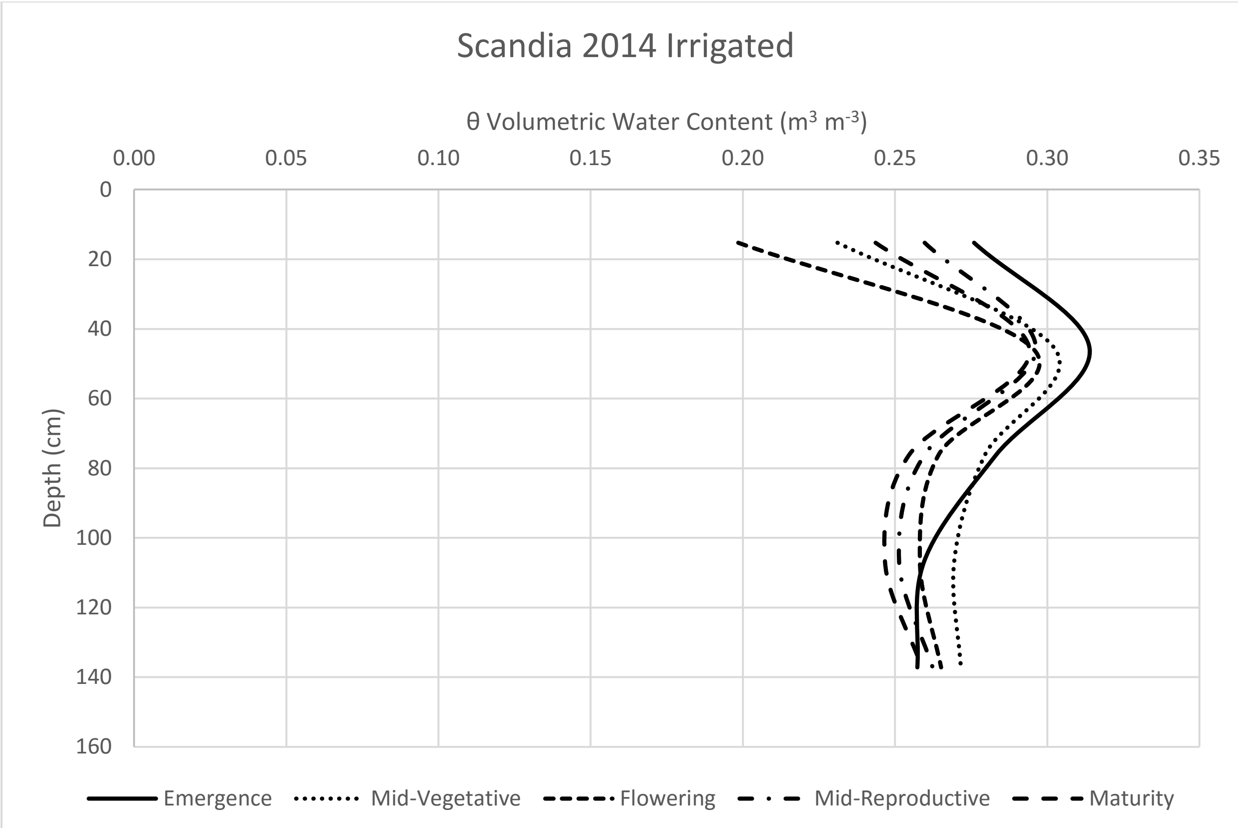
Hutchinson 2014 Irrigated
θ Volumetric Water Content (m^3 m^{-3})
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Depth (cm)
0
20
40
60
80
100
120
140
160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

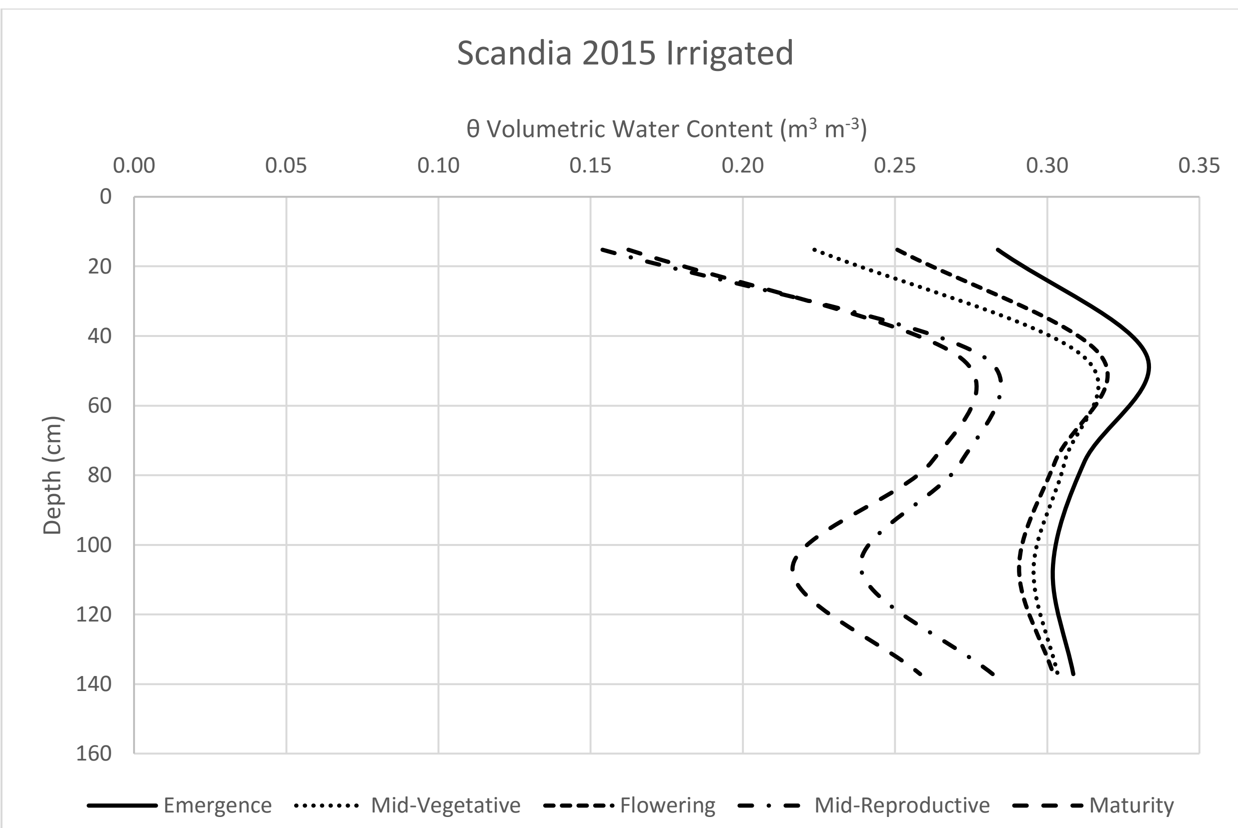


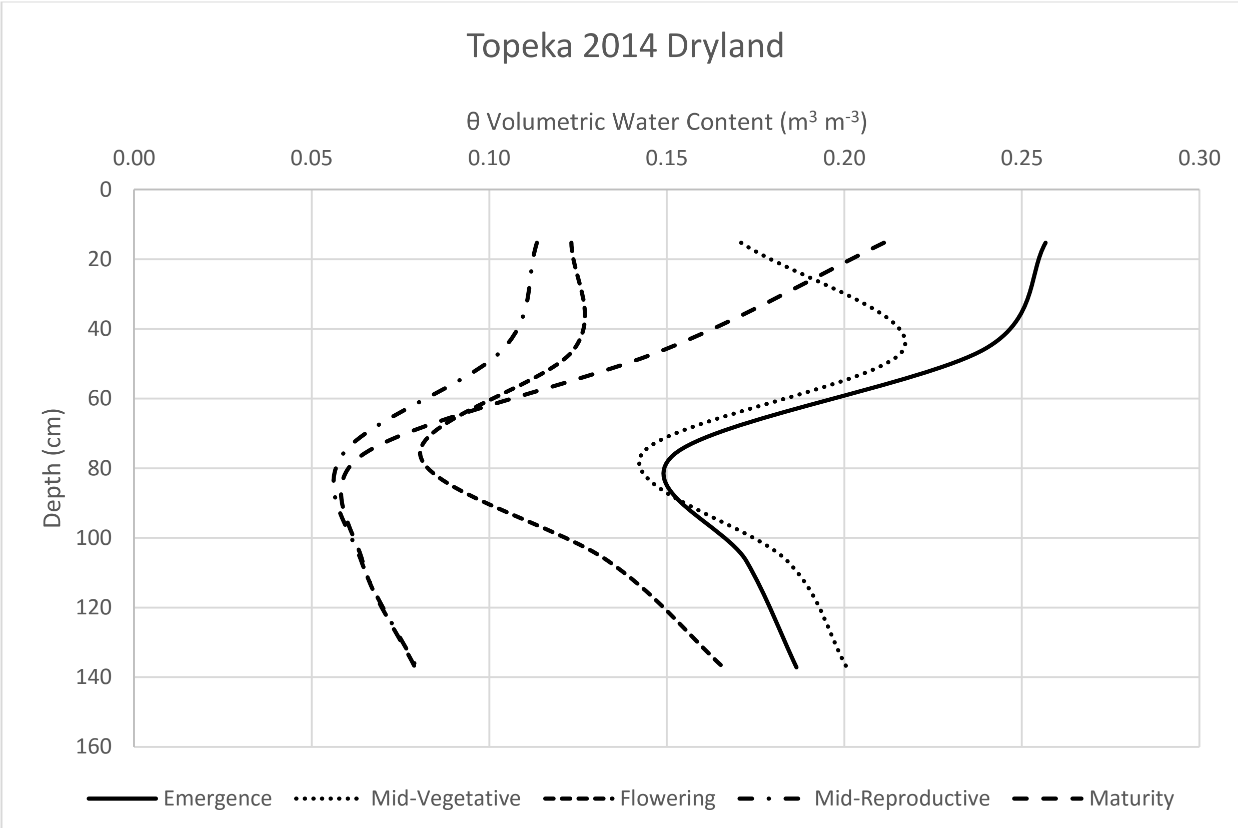
Hutchinson 2015 Irrigated
θ Volumetric Water Content (m^3 m^{-3})
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Depth (cm)
0
20
40
60
80
100
120
140
160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

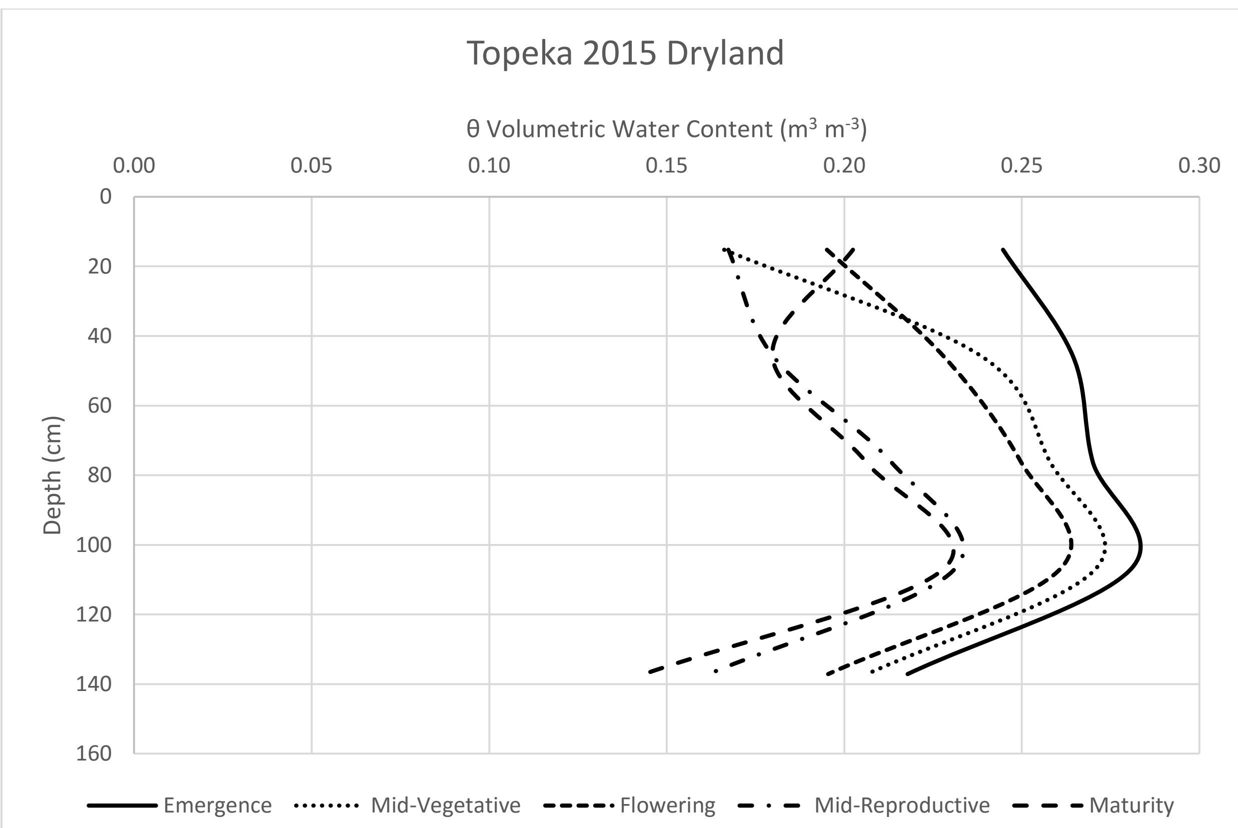

Scandia 2014 Dryland
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
20
40
60
80
100
120
140
160
Depth (cm)
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

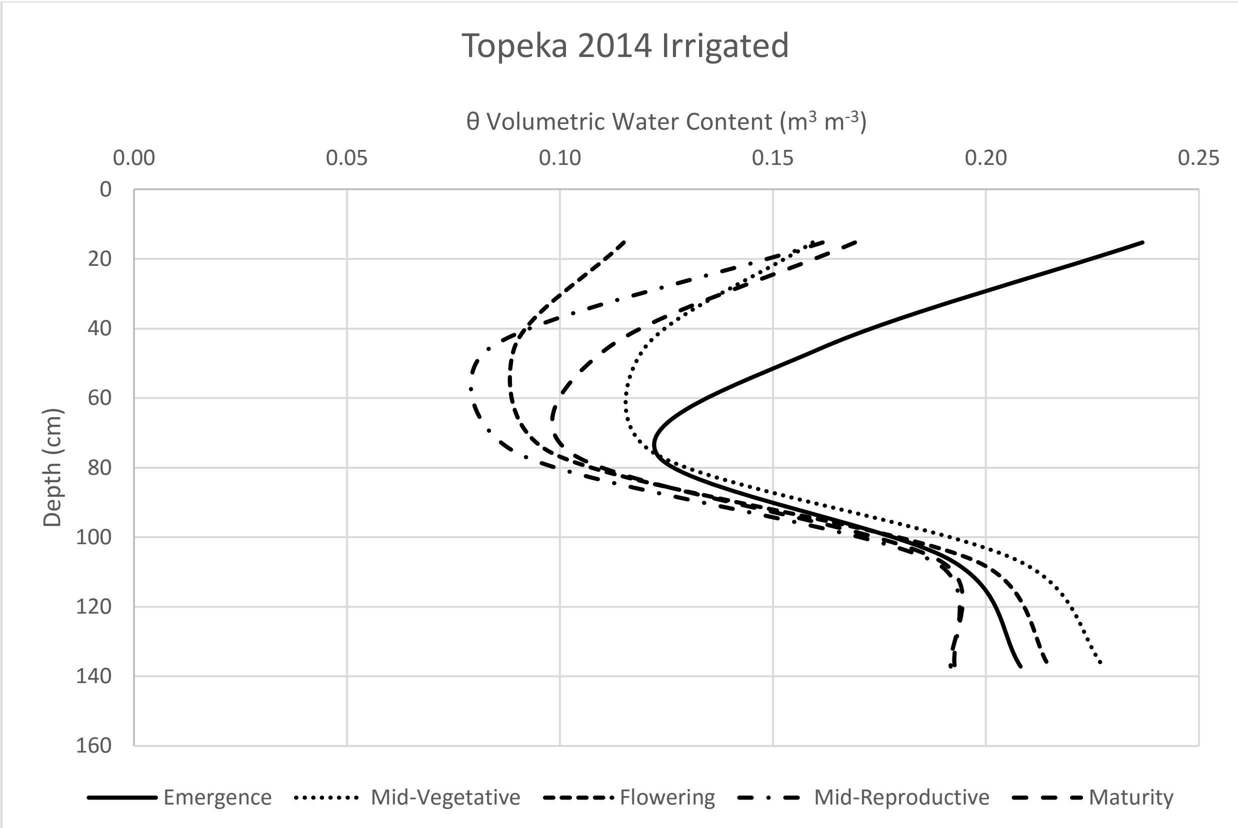

Scandia 2015 Dryland
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
20
40
60
80
100
120
140
160
Depth (cm)
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

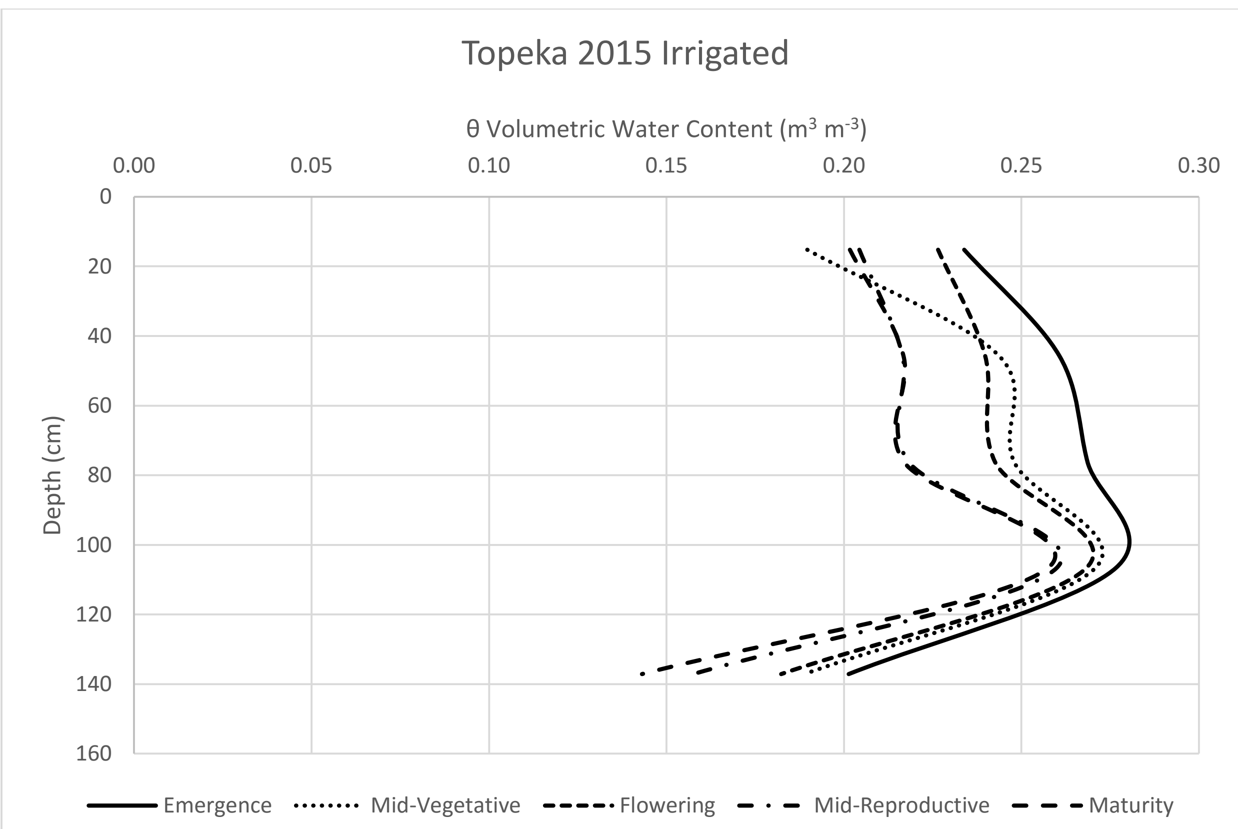

Scandia 2014 Irrigated
θ Volumetric Water Content (m³ m⁻³)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
20
40
60
80
100
120
140
160
Depth (cm)
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

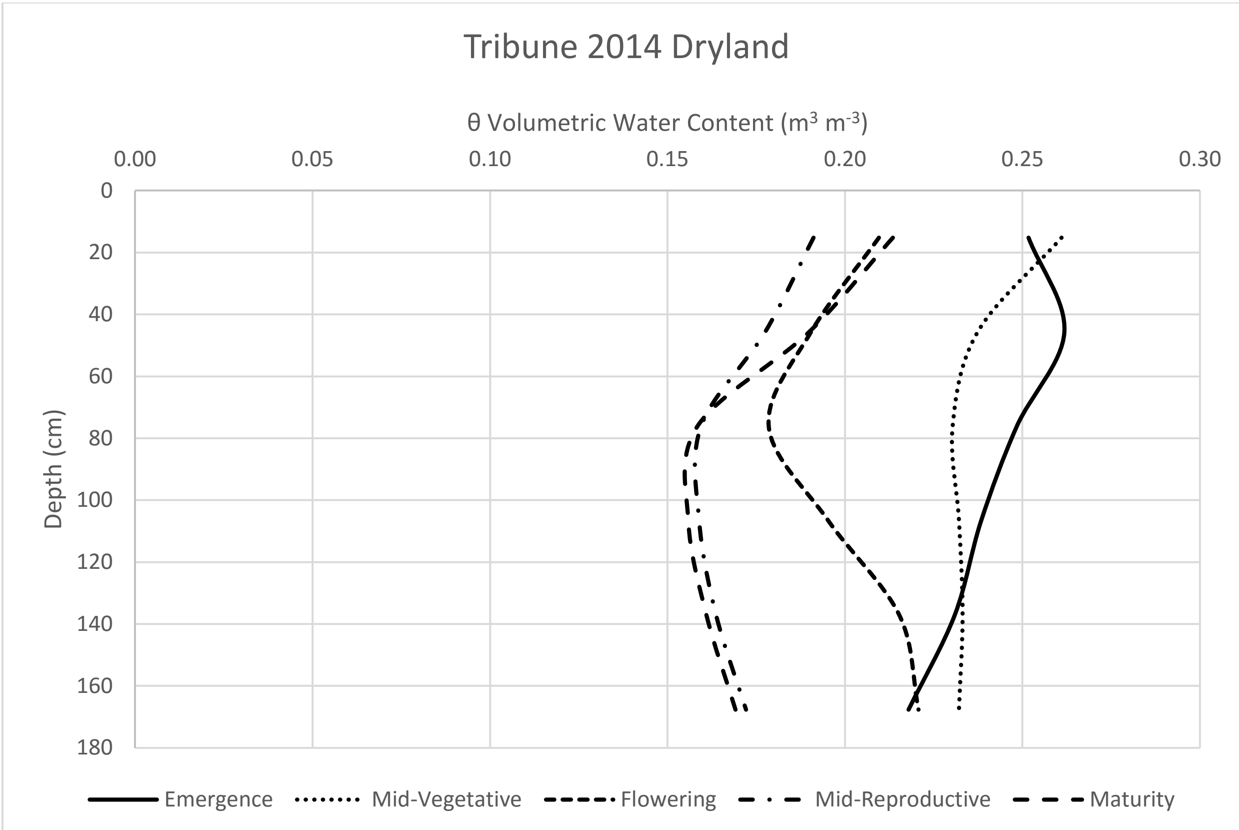

Scandia 2015 Irrigated
θ Volumetric Water Content (m³ m⁻³)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
20
40
60
80
100
120
140
160
Depth (cm)
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Topeka 2014 Dryland
θ Volumetric Water Content (m³ m⁻³)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Depth (cm)
0
20
40
60
80
100
120
140
160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Topeka 2015 Dryland
θ Volumetric Water Content (m³ m⁻³)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Depth (cm)
0
20
40
60
80
100
120
140
160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Topeka 2014 Irrigated
θ Volumetric Water Content (m³ m⁻³)
0.00 0.05 0.10 0.15 0.20 0.25
Depth (cm)
0 20 40 60 80 100 120 140 160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Topeka 2015 Irrigated
θ Volumetric Water Content (m³ m⁻³)
0.00 0.05 0.10 0.15 0.20 0.25 0.30
Depth (cm)
0 20 40 60 80 100 120 140 160
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity


Tribune 2014 Dryland
θ Volumetric Water Content (m3 m-3)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
20
40
60
80
100
120
140
160
180
Depth (cm)
Emergence
Mid-Vegetative
Flowering
Mid-Reproductive
Maturity

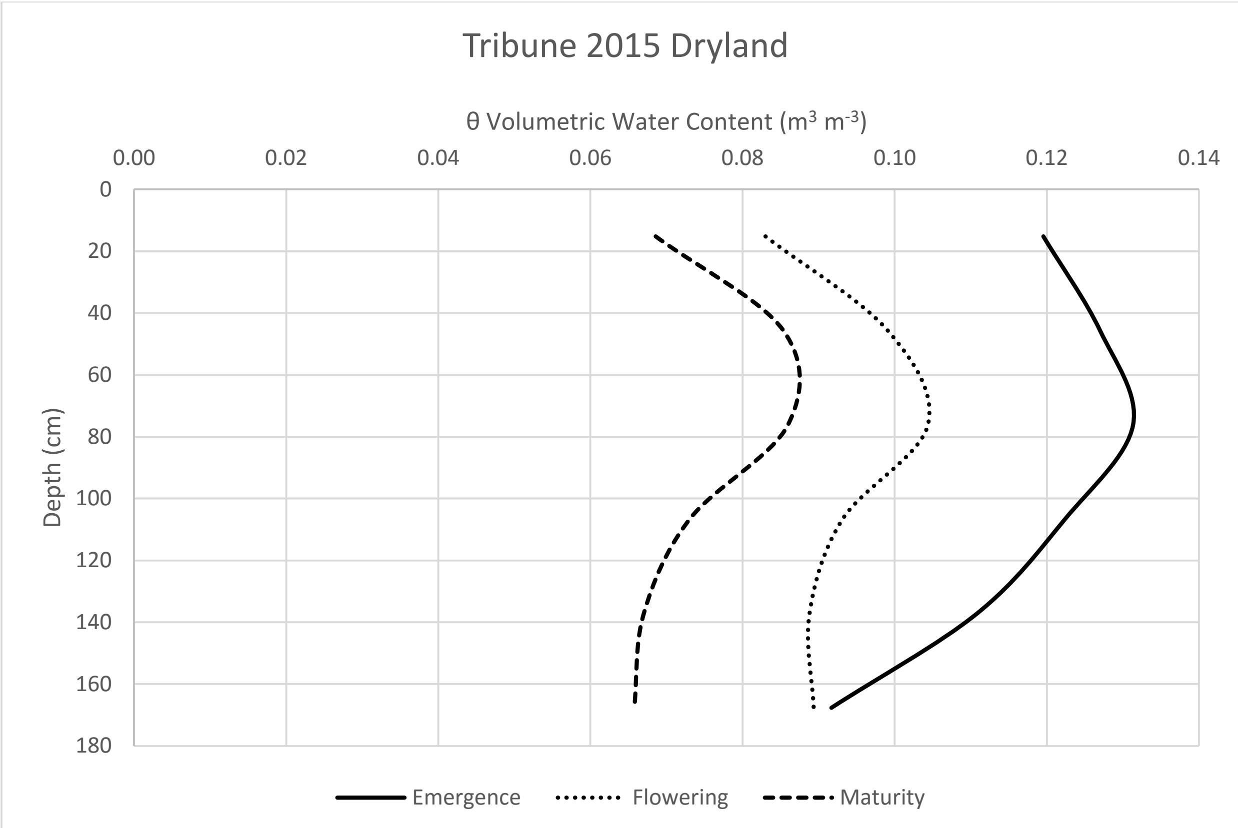


Figure 2.18 Graphs for the Volumetric Water Content Data throughout the Soil Profile at each Physiological Growth Stage Measured for all Environments in 2014 and 2015.